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Manual for Land Application of Treated Municipal Wastewater and Sludge

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MANUAL FOR LAND APPLICATION OF TREATED MUNICIPAL WASTEWATER AND SLUDGE

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FOREWORD

The need for this information manual was identified at a "Workshop on Effluent Irrigation" held in Regina, Saskatchewan, November 6, 1980. Development of the document was initiated by Mr. H.J. Brian Curran, EPS, Saskatchewan District Office. Several provincial and federal agencies involved in land use, public health and environmental conservation responded to an enquiry in 1981 and both a Technical Working Group (TWG) and a Review Group were organized. Each member of the TWG was assigned lead responsibility for one or more sections of the document. Meetings of the TWG were held in Calgary, Winnipeg, Vegreville, Swift Current and Burlington. The Review Group, which included representatives from all provincial governments, the federal government and selected universities, were asked to consider the expanded outline and a draft of the information manual.

The purpose of the manual is to provide basic information for individuals and organizations interested in the application of treated municipal wastewater and sludge to land. The manual is not a design guide; current engineering practice must be employed for design purposes.

AVANT-PROPOS

Le présent guide d'information a été conçu à l'"Atelier sur l'irrigation au moyen d'effluents" tenu le 6 novembre 1980 à Régina. M. H.J. Brian Curran du SPE, bureau de district de la Saskatchewan, a amorcé le développement de ce document. En 1981, plusieurs organismes provinciaux et fédéraux chargés de l'utilisation des terres, de la santé publique et de conservation de l'environnement ont été consultés et un groupe de travail technique (GTT) et un groupe d'étude ont été créés. Chaque membre du GTT a été affecté à la direction d'au moins une des sections de ce document. Le GTT s'est réuni à Calgary, Winnipeg, Vegreville, Swift Current et Burlington. On a demandé au groupe d'étude, incluant des représentants de tous les gouvernements provinciaux et fédéral ainsi que de quelques universités choisies de prendre en considération le plan détaillé et l'ébauche du guide.

Ce guide s'adresse aux individus et organisations qui s'intéressent à l'épandage, sur les terres, des eaux usées et des déchets urbains traités. Il ne s'agit pas d'un guide de conception technique pour laquelle on recourra plutôt à l'art de l'ingénieur.

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1 INTRODUCTION

1.1 Background

Land application of treated municipal wastewater and sludge can provide an economic and environmentally acceptable method of disposal for these materials.

Treated municipal wastewater can be used to supplement the natural water supply available for agricultural crops. Application during periods of soil moisture deficit will increase crop productivity. In addition, the nutrients in wastewater, particularly nitrogen and phosphorus, supplement soil nutrients and may reduce the requirement for commercial fertilizer.

Sludge application to land provides a significant nitrogen and phosphorus nutrient benefit. Approximately one-third of the nitrogen in liquid anaerobically digested sludge is immediately available to crops, and much of the balance becomes available with time. Consequently, the sludge maintains plant-available nitrogen in the root zone for a longer period of time than most commercial fertilizers. Chemical treatment of wastewater for phosphorus removal enhances the phosphorus concentration in sludge. A single application of this sludge may meet the phosphorus requirements of crops for four to five years.

When considering a land application program for treated municipal wastewater or sludge, it is important to remember that success will depend upon public acceptance. Often resistance arises when a poor public image is presented. This can occur if:

- a public relations program is inadequate;
- a system is poorly designed;
- the public has previously had a bad experience with the proponent or the type of project being proposed;
- the public questions the ability of the proponent to operate the proposed system.

Public relations, while important, is unlikely to convince the public to accept a poorly planned project. A successful project will require input from a team with expertise in wastewater treatment systems, agronomics, transportation and spreading systems, and public relations. This manual identifies the principal areas of concern that should be addressed in developing a land application project for treated wastewater or sludge.

1.2 Purpose

The purpose of this manual is to consolidate state-of-the-art information about land application of treated municipal wastewater and sludge into one comprehensive document. The manual addresses the technical concerns associated with treatment, transport, spreading, agronomics and health. It also discusses legal, social and economic concerns and the need to obtain a clear indication of potential benefits and risks. However, the document is not a design guide. Engineering expertise must be employed to ensure that land application systems meet standards prescribed by the appropriate governing agencies.

1.3 Scope

In so far as possible the manual discusses all aspects of the application of treated municipal wastewater and sludge to land. The various concerns are addressed in individual sections. Section 2 discusses planning considerations that should be considered prior to undertaking any land application program. Section 3 provides a general discussion of wastewater treatment and Sections 4 to 6 describe soil, environmental health and crop considerations. Finally, Sections 7 and 8 address technical aspects of land application of treated municipal wastewater and sludge, respectively.

Although the manual deals primarily with treated municipal wastewater and sludge, the information it provides may be applicable to the disposal of treated wastewaters and sludges from a number of industrial processes (e.g., food processing - canning, dairy products, meat packing).

1.4 Use of the Manual

The manual is intended to be of value to wastewater treatment plant operators, farmers, sanitary engineers, municipal authorities, regulatory agencies, and public interest groups, and of use:

- in the preliminary evaluation of treatment alternatives,
- in the preparation of public information packages,
- in responding to public requests or concerns,
- as an aid in the design and operation of land application projects.

A user with a specific interest can read the appropriate section(s) to obtain the information required.

2 PLANNING CONSIDERATIONS

This section identifies planning considerations that should be addressed prior to implementing a land application program for treated municipal wastewater or sludge. It is suggested that planning occur in four more or less well-defined stages as follows:

1) preliminary evaluation,
2) detailed project evaluation,
3) formal hearings and approval, and
4) final design considerations.

The preliminary evaluation should be done by someone with a general knowledge of the municipality in conjunction with the regulatory authority. Existing information is used and the problems that exist and potential solutions are considered in a preliminary review. The desirability of entering into a more detailed study is determined. The entire preliminary evaluation should take only about three days.

Projects that survive a preliminary evaluation should proceed to a detailed project evaluation. At this stage, public input should be solicited. The detailed project evaluation responds to the same general questions as the preliminary evaluation but the review is more substantial. In general, a detailed evaluation will require considerable time and expertise, and will involve consultants. Samples may have to be collected and analysed to determine the characteristics of the wastes being considered. Data analysis and interpretation will be necessary to determine which options deserve consideration for final design. Estimated prices and land requirements should be prepared.

Following the detailed project evaluation, a decision should be taken whether to proceed with the project. Assuming a positive decision is made, and formal approval is obtained, a detailed design should be prepared.

2.1 Preliminary Evaluation

Several subject areas requiring consideration during a preliminary evaluation of a land application project are identified in Figure 1.

2.1.1 Problem Definition. Before proceeding to an evaluation of alternative wastewater and sludge disposal systems, problems with the existing system should be defined. They may include social, environmental or economic unacceptability, or noncompliance with pollution control regulations. For example, current practice may be causing environmental damage and public action groups may be pressing for change.

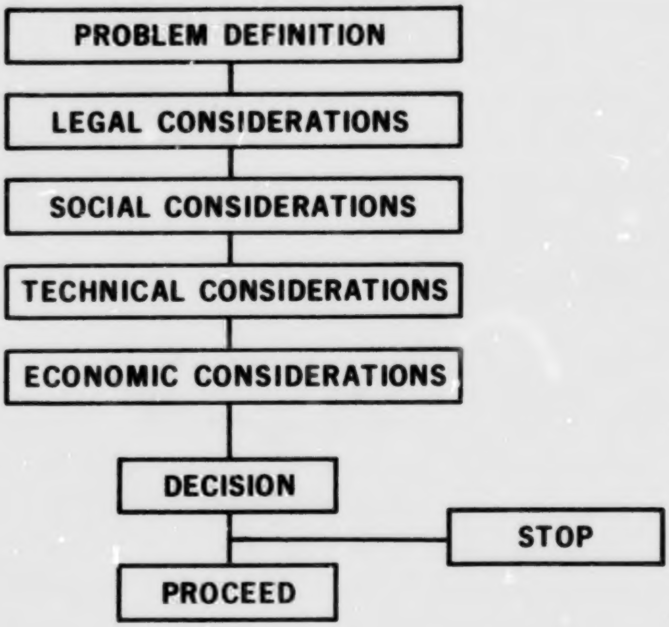

PROBLEM DEFINITION
LEGAL CONSIDERATIONS
SOCIAL CONSIDERATIONS
TECHNICAL CONSIDERATIONS
ECONOMIC CONSIDERATIONS
DECISION
STOP
PROCEED

FIGURE 1 PRELIMINARY EVALUATION

Alternatively, recently revised environmental legislation may require upgrading of the wastewater treatment facility and changes in sludge disposal practice.

Where future growth is likely in the municipality, it is possible that wastewater and sludge disposal problems could develop in the future due to increased population. The age of existing equipment or probable changes in bylaws or regulations are additional factors.

2.1.2 Legal Considerations. Provincial or municipal regulations may prevent the land application of treated wastewater or sludge. For example, as of 1984 land application of sludge was illegal in the province of Québec. Alternatively, municipal zoning may prohibit application in selected areas. Where land application is found to be illegal, it will be necessary to effect a change in the legislation or to abandon further consideration of this disposal alternative.

2.1.3 Social Considerations. It is important to gauge public opinion as to the acceptability of a project. Public response will vary with the nature of the municipality. For example, communities with a large non-farming rural population are likely to offer resistance due to perceived odour and environmental problems. In addition to the general public, the attitude of the local farming community should be considered. Land application may or may not complement local agricultural practices; however, the potential for acceptance is likely to increase if evidence for economic benefit can be presented.

Finally, consideration should be given to whether potential problems can be discussed with the public and a suitable program developed. The existence of a very negative attitude may preclude the use of land application and, if so, the evaluation should be terminated.

2.1.4 Technical Considerations. Consideration should be given to whether the treated wastewater or sludge is suitable for land application. If the municipality has a large industrial sector, the sludge may be unsuitable due to high concentrations of heavy metals or other hazardous constituents.

Storage facilities to hold treated wastewater or sludge will be required for periods when land application is not possible due to climate, weather conditions, cropping requirements, etc. Would such storage facilities receive approval and are they economically feasible?

Land area requirements must be estimated and land availability and suitability assessed. Land for treated municipal wastewater application should fall within 5 to 10 km of the treatment facility, and land for sludge application should fall within 50 km.

2.1.5 Economic Considerations. The cost of conducting a detailed land application project evaluation should be estimated. This should include municipal staff input and consulting fees, and specific expenditures such as analytical testing and public information programs. These costs must be acceptable to the municipality.

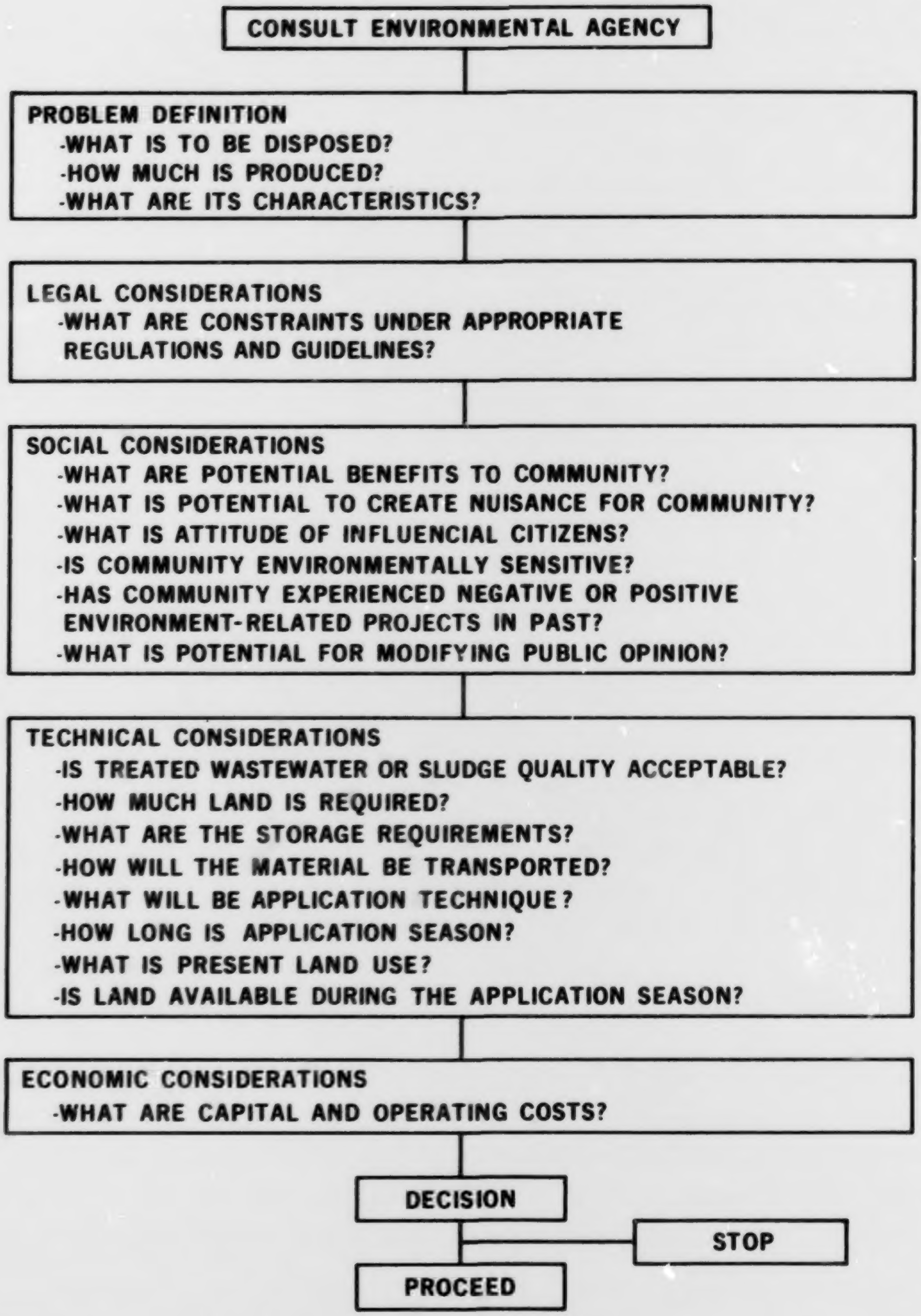
If there are no obvious economic reasons that a land application program should not be considered, then a detailed project evaluation should be undertaken.

2.2 Detailed Project Evaluation

Before commencing a detailed project evaluation, the appropriate environmental regulatory agency (Appendix A) should be consulted to identify specific requirements that the agency has for project approval.

Various considerations comprising a detailed project evaluation are presented in Figure 2.

2.2.1 Project Definition. A detailed account of the quantity and characteristics of the material to be disposed should be prepared. If data are not available, this will require



CONSULT ENVIRONMENTAL AGENCY

PROBLEM DEFINITION
- WHAT IS TO BE DISPOSED?
- HOW MUCH IS PRODUCED?
- WHAT ARE ITS CHARACTERISTICS?

LEGAL CONSIDERATIONS
- WHAT ARE CONSTRAINTS UNDER APPROPRIATE REGULATIONS AND GUIDELINES?

SOCIAL CONSIDERATIONS
- WHAT ARE POTENTIAL BENEFITS TO COMMUNITY?
- WHAT IS POTENTIAL TO CREATE NUISANCE FOR COMMUNITY?
- WHAT IS ATTITUDE OF INFLUENCIAL CITIZENS?
- IS COMMUNITY ENVIRONMENTALLY SENSITIVE?
- HAS COMMUNITY EXPERIENCED NEGATIVE OR POSITIVE ENVIRONMENT-RELATED PROJECTS IN PAST?
- WHAT IS POTENTIAL FOR MODIFYING PUBLIC OPINION?

TECHNICAL CONSIDERATIONS
- IS TREATED WASTEWATER OR SLUDGE QUALITY ACCEPTABLE?
- HOW MUCH LAND IS REQUIRED?
- WHAT ARE THE STORAGE REQUIREMENTS?
- HOW WILL THE MATERIAL BE TRANSPORTED?
- WHAT WILL BE APPLICATION TECHNIQUE?
- HOW LONG IS APPLICATION SEASON?
- WHAT IS PRESENT LAND USE?
- IS LAND AVAILABLE DURING THE APPLICATION SEASON?

ECONOMIC CONSIDERATIONS
- WHAT ARE CAPITAL AND OPERATING COSTS?

FIGURE 2 DETAILED PROJECT EVALUATION

measurement of flow and wastewater and sludge production rates, and sampling and analysis.

2.2.2 **Legal Considerations.** Federal, provincial and municipal regulations or guidelines (Appendix A) may specify limitations on the development of the proposed land application program. These limits should be identified in detail, including such factors as the areas in which the program can be developed, the rates at which the materials can be spread, separation distances required from residences, wells, streams, etc. and constraints on the spreading of specific substances such as nitrogen, phosphorus, heavy metals and chloride.

2.2.3 **Social Considerations.** At this point in the project evaluation it is important to establish contact with the public to inform them concerning the proposed project. The following concerns should be addressed.

A project must generate benefit to the community. Benefits from land application of treated wastewater might include improved receiving water quality, expanded recreational opportunities, reduced wastewater treatment costs and increased agricultural production. Sludge application benefits might include reduced sludge handling costs and provision of a cheap agricultural fertilizer material.

The ways in which the project might detract from the quality of life in the community must also be considered. These could include odour problems, increased truck traffic, visual impairment due to sludge spreading or wastewater irrigation, or spray drift from wastewater irrigation. Every project will have some potential for nuisance. This potential should be identified early in the planning process.

In every community there is a core group of influential citizens who will tend to lead support or opposition for a project. These people include professionals, politicians, heads of ratepayer associations and others. As part of the social evaluation, these people should be identified and their support solicited.

In planning a project, some thought should be given to the probable environmental attitude within the community. In agricultural areas there is likely to be acceptance for a program that will benefit the agricultural economy. By comparison, areas with large numbers of non-farming rural residents are likely to offer resistance due to perceived problems of odour and environmental contamination. The social mix of the area should be considered and the probable reaction projected.

Communities with successful waste management programs that have a proven environmental record are likely to be more amenable to land application than communities with no previous experience or unsatisfactory previous experience. For example, the South Cayuga area in Ontario was recently the target for development of a hazardous waste disposal site. The site was not established, but this community is now highly organized and prepared to fight any project perceived as an environmental threat. To establish a project in such a location would require extensive discussions and verification to demonstrate its acceptability. If there is opposition, the potential for gaining acceptance for a land application project should be assessed. This would include identifying reasons for the opposition and the time and expertise required to overcome it. Estimates of the fertilizer value of sludge, and of the irrigation and fertilizer value of treated wastewater are likely to be valuable selling points.

2.2.4 **Technical Considerations.** The appropriate regulations or guidelines (Appendix A) should be identified to determine whether the treated wastewater or sludge meets the quality requirements for land application. If the quality of the wastewater or sludge is unacceptable and application is illegal or rates would have to be reduced to comply with legal limits, the possibility of improving the quality should be considered. For example, unacceptably high heavy metal concentrations in sludge may be reduced by pretreatment of metal industry wastewaters.

The land area requirement should be estimated assuming application rates recommended in the appropriate guidelines. Land would have to be available in a suitable location. More than the minimum required area should be available to compensate for fields that cannot be used during part of the spreading season due to weather conditions, cropping or other agronomic factors. In selecting sites for a land application program, it is necessary to ensure that the distances from such features as urban development, single dwellings, water wells, streams, etc. are adequate.

Storage lagoons are frequently used to retain treated wastewater in winter and early spring or following heavy rain when land application is inappropriate. Similarly, sludge must be stored or disposed of by an alternative method when it cannot be applied to land. Consideration should be given to how much storage capacity will be required and whether suitable storage facilities can be constructed. It may be more difficult to obtain approval for the construction of storage facilities than for the establishment of the land application program, particularly if the proposed facilities are not adjacent to the land application site.

Moving the material from the wastewater treatment facility to the land application site poses a significant problem. Usually treated wastewater is transported in temporary or permanent pipelines. By contrast, sludge is transported in tank trucks and transferred to spreading vehicles on-site or is transported in combination haul-spread vehicles. The selection of a transportation mode depends on a variety of factors, including type and amount of material, transport distance and time constraints. Residential development, road use restrictions and increased road maintenance must be considered in relation to truck transport.

Treated wastewater is usually applied to land by sprinkler irrigation. Standard irrigation equipment is used and it can be manual or automated, portable or stationary. System selection will depend on capital and manpower availability. There is likely to be more spray drift away from application sites with high pressure systems than with low pressure systems.

Sludge is usually applied as liquid from a wheeled vehicle. The most satisfactory spreading vehicles have pressure discharge tanks and flotation tires. This combination permits uniform application of the sludge and minimizes soil compaction, especially on medium to heavy textured soils. Liquid sludge can also be irrigated onto land using a high-volume gun, but this technique is aesthetically unpleasant and may result in spray drift. Dewatered sludge is usually spread on land with agricultural manure spreading equipment. Soil compaction is minimized if the equipment has flotation tires.

Climate, weather and local farming practices will dictate when wastewater or sludge can be land applied. The length of the application season should be estimated.

Consideration should be given to land use practices in the proposed application area. Forage cropping systems are particularly suited to wastewater irrigation because they have larger water requirements than most other crops. Fallow and pasture land can receive sludge at any time during the application season; however, a delay between application on pasture land and grazing is recommended to avoid disease or parasite transfer to animals. The availability of cash crop land for sludge application will depend upon seeding and harvest dates. Sludge should not be applied following seeding, except perhaps by injection into row crop land early in the growing season. Availability of land throughout the application season is desirable because the requirements for storage facilities and application equipment and manpower can be minimized.

2.2.5 **Economic Considerations.** Detailed estimates including both capital and operating costs should be developed for the project. Operating costs must be included because they can change significantly with transportation distance. A project may appear desirable until the combined capital and operating cost is amortized. The cost of the land application program should be compared with the cost of other alternatives.

2.3 Formal Hearings and Approval

The results of the detailed project evaluation should be presented to the community and regulatory agencies. Subsequently, time should be allowed to respond to criticism and requests for further information. The decision can then be made whether to proceed with the final design.

2.4 Final Design

The various design considerations that are required to finalize a project are presented in Figure 3.

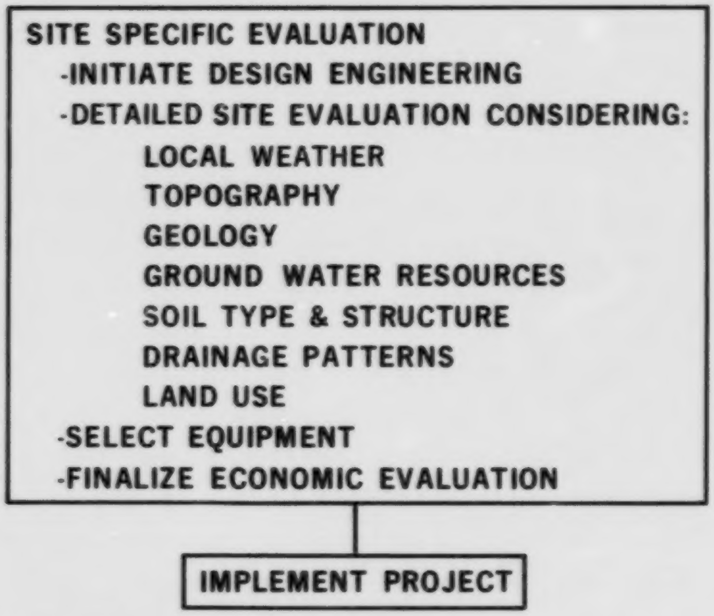

SITE SPECIFIC EVALUATION
-INITIATE DESIGN ENGINEERING
-DETAILED SITE EVALUATION CONSIDERING:
LOCAL WEATHER
TOPOGRAPHY
GEOLOGY
GROUND WATER RESOURCES
SOIL TYPE & STRUCTURE
DRAINAGE PATTERNS
LAND USE
-SELECT EQUIPMENT
-FINALIZE ECONOMIC EVALUATION
IMPLEMENT PROJECT

FIGURE 3 FINAL DESIGN

At this point, design engineering is initiated. This includes detailed site evaluations taking into account the local weather conditions, topography, geology, soil type and structure, drainage patterns, groundwater resources and land use. Assuming that suitable sites can be located, a specific system is selected and design initiated. The choice of spreading equipment and application rates will allow the economic evaluation to be finalized.

3 WASTEWATER TREATMENT AND DISPOSAL

The information contained in this section is intended to familiarize the reader with the principle treatment processes involved in producing treated municipal wastewaters and sludges in Canada.

3.1 What is Wastewater and Why is Treatment Necessary?

Wastewater contains materials which pollute natural waters. It is composed of domestic sewage collected from households, commercial enterprises and institutions, and process waters collected from industrial operations.

Domestic sewage contains solids, readily decomposable organic materials, nutrients (mainly nitrogen and phosphorus), surfactants (detergents) and pathogenic organisms (bacteria, viruses and parasites). Industrial process waters vary in composition depending on the industry and may contain various hazardous substances such as heavy metals and toxic organic compounds.

Wastewater treatment removes undesirable constituents and is undertaken to protect public health and maintain the aesthetic quality of the environment. It reduces the risk of disease arising from waterborne pathogenic organisms and the release of noxious substances to the environment.

3.2 Treatment Options

Wastewater treatment options vary depending upon the size of the community being served. Small communities usually employ lagoons which do not involve mechanical equipment and are simple to operate and maintain. However, they require large land areas (0.4 hectares per 100 people) and are not economical for large populations. Medium and large communities generally employ mechanical treatment systems. Mechanical wastewater treatment plants can incorporate different degrees of treatment, usually referred to as primary, secondary and tertiary, depending upon the degree of treatment required.

3.2.1 **Wastewater Treatment Lagoons.** More than 700 municipal wastewater treatment lagoons of various sizes, shapes and retention times are in operation in Canada (Environment Canada, 1981). They usually consist of simple earthen basins and are excavated into the natural soil or are built above grade by constructing earth berms. Lagoons constructed in other than clay soils are lined with clay or a synthetic material to reduce leakage.

Figure 4 shows a cross-section of a wastewater treatment lagoon. Raw wastewater is discharged into one end of the lagoon and, following a retention time in the order of 30 days, treated wastewater is released from the other end. During retention, several processes occur which contribute to treatment. Solid materials settle and collect as sludge on the lagoon floor. Algae grow, removing nutrients from and releasing oxygen to the wastewater. Aerobic microorganisms grow and convert oxygen demanding organic materials in the wastewater to stable substances that do not harm the ecology of the receiving waters. The sludge undergoes anaerobic decomposition and seldom, if ever, has to be removed.

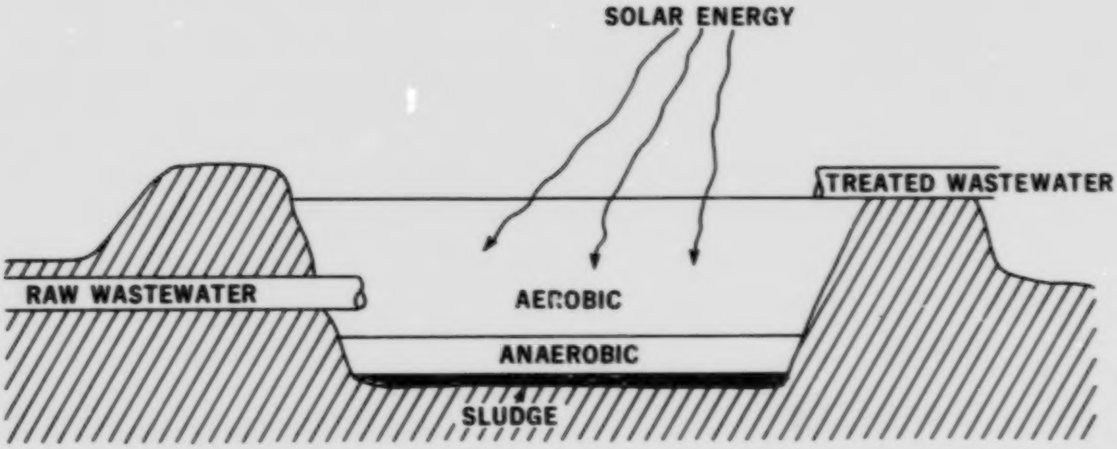


FIGURE 4 WASTEWATER TREATMENT LAGOON

The treatment efficiency of lagoons varies during the year. In summer it is high but during the winter and early spring when temperatures are low and the lagoon may be covered with ice or snow, it is low. The overall quality of wastewater released depends upon the number of lagoons available (i.e., storage capacity) and the operating strategy employed.

3.2.2 Mechanical Treatment Systems. Mechanical wastewater treatment systems are depicted in Figure 5.

Mechanical systems usually include primary treatment which involves the separation of solid substances from wastewater by settling. The wastewater is treated in

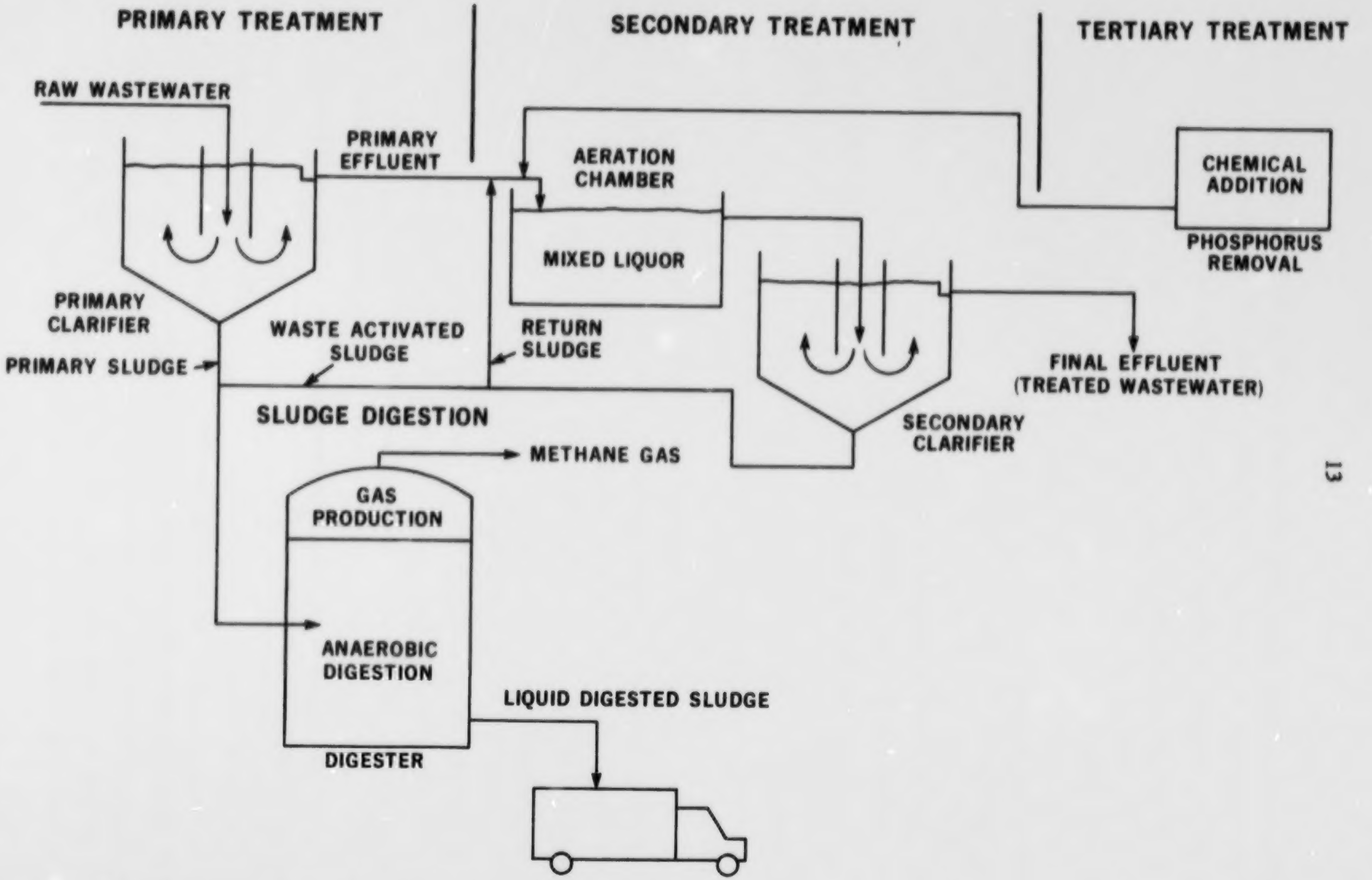

PRIMARY TREATMENT
SECONDARY TREATMENT
TERTIARY TREATMENT
RAW WASTEWATER
PRIMARY EFFLUENT
AERATION CHAMBER
CHEMICAL ADDITION
MIXED LIQUOR
PHOSPHORUS REMOVAL
PRIMARY CLARIFIER
WASTE ACTIVATED SLUDGE
RETURN SLUDGE
PRIMARY SLUDGE
FINAL EFFLUENT (TREATED WASTEWATER)
SLUDGE DIGESTION
SECONDARY CLARIFIER
METHANE GAS
GAS PRODUCTION
ANAEROBIC DIGESTION
LIQUID DIGESTED SLUDGE
DIGESTER

FIGURE 5 MECHANICAL WASTEWATER TREATMENT

a clarifier (holding tank) with a retention time in the order of 0.5 to 1.5 hours. Forty to 55% of the suspended solids (SS) and 15 to 30% of the organic materials requiring oxygen (BOD) are removed during primary treatment. The settled solids (primary sludge) are transferred to a sludge digester.

Secondary treatment removes soluble and colloidal organic substances remaining in the primary effluent. There are several secondary treatment methods but the one most commonly used in Canada is the activated sludge process. In this process aerobic microorganisms mix with the primary effluent to form "mixed liquor" and use the organic substances as food. The mixed liquor is aerated in a chamber for three to eight hours during which microbial growth occurs. It is subsequently transferred to a secondary clarifier where the microorganisms concentrate on the bottom producing a sludge and the effluent is discharged to a watercourse or undergoes tertiary treatment.

Most of the secondary clarifier sludge is returned to the aeration tank to maintain the required concentration of microorganisms. The excess sludge is wasted to the digester.

Other less common methods of secondary treatment include trickling filters and rotating biological contactors.

The purpose of tertiary treatment is to treat wastewater beyond the level attained with primary and secondary processes. Tertiary treatment can include a number of different processes, each designed to remove a specific pollutant. Typical tertiary treatment processes are chemical addition, sand filtration, nitrification-denitrification, and carbon adsorption.

Tertiary treatment processes can be integrated into the wastewater treatment plant at a number of locations. Chemical addition for phosphorus removal is the most common tertiary treatment operation and usually is done either in the primary clarifier or aeration chamber. Sand filtration, nitrification-denitrification and carbon adsorption are undertaken as final treatment steps. Sand filtration removes suspended solids; nitrification-denitrification removes nitrogen; and carbon adsorption removes soluble organic compounds.

3.2.3 **Sludge Treatment.** Solids collected in the clarifiers (primary sludge and waste activated sludge) are pumped to a digester for further treatment. The sludge can be treated either in the presence of oxygen (aerobically) or in the absence of oxygen (anaerobically). The majority of sludge treatment facilities employ anaerobic digestion. In this process, the sludge is retained in the absence of oxygen at approximately 30°C for about 30 days. Decomposition of organic solids occurs and methane gas is produced. The total mass of sludge is reduced by approximately 40% and there is a considerable reduction in the numbers of pathogenic organisms.

3.3 Quantities and Properties of Wastewater Treatment Products

3.3.1 **Treated Effluent.** A recent Ontario survey (Schmidtke, 1981) indicates that average wastewater flows are in the order of 500 to 660 litres per person per day. Assuming a population of 30 000 people and a flow of 600 litres per person per day, the volume of treated effluent would be 18 000 m^3 per day.

The treated wastewater quality is a function of the treatment provided, the operating strategy employed, and the characteristics of the raw wastewater. Consequently, treated wastewaters exhibit wide variations in quality, as indicated by the data for selected properties in Table 1.

TABLE 1 TYPICAL PROPERTIES OF TREATED MUNICIPAL WASTEWATER

Parameter	Units	Untreated Wastewater	Primary Treatment	Lagoon Effluent	Mechanical Plant Effluent
Fecal Coliform	Number/ 100 mL	1×10^6 to 2×10^7	3×10^5 to 6×10^6	2×10^2 to 1×10^5	6×10^3 to 2×10^5
BOD_5	mg/L	200	130 - 150	15 - 100	10 - 40
Suspended Solids	mg/L	230	80 - 120	15 - 100	10 - 35
Total N[a]	mg/L	30 - 40	20 - 30	3 - 26	15 - 25
Total P[b]	mg/L	8 - 12	7 - 9	1.4 - 9.0	3 - 7
Total K	mg/L	-	-	4.0 - 30	7 - 10
pH		-	-	6.5 - 9.4[c]	6.8 - 8.1
EC[d]	dS/m	-	-	0.6 - 3.5	0.8 - 1.0
SAR[e]	meq/L	-	-	2 - 60	-

[a] Nitrogen (N) and phosphorus (P) values tended to be lower in the summer. This is probably due to the higher pH values which result in increased volatilization of ammonia and precipitation of calcium phosphate.

[b] Treatment plants employing P removal will produce an effluent with concentrations near 1 mg P/L.

[c] Lagoon effluent pH will vary with time of year and the amount of algal growth. Generally warmer periods with more growth result in higher pH values.

[d] Electrical conductivity (EC) is a function of raw water EC, infiltration into collection lines, and evaporation during treatment.

[e] Sodium Adsorption Ratio (SAR) = $Na/\sqrt{(Ca + Mg)/2}$

3.3.2 Treated Sludge. The mass of sludge produced depends upon the degree of wastewater treatment. Ontario data (Schmidtke, 1981) indicate that the production of raw sludge, measured as dry solids, is approximately 80 grams per person per day for a primary treatment plant compared to 115 grams per person per day for a secondary treatment plant and 145 grams per person per day for a secondary treatment plant with chemical addition for phosphorus removal (tertiary treatment).

Assuming that anaerobic digestion reduces the mass of sludge solids by 30 percent, the solids requiring disposal from a community of 30 000 people with secondary wastewater treatment would be 3.5 tonnes per day. Liquid anaerobically digested sludge may vary from 2 to 9% solids, but assuming 4% solids, the volume of sludge requiring disposal would be approximately 90 m^3/d.

Typical properties of anaerobically digested sludges are presented in Table 2. Differences in heavy metal concentrations between primary and secondary sludges (e.g. Cr) are probably due to differences in raw wastewater quality rather than degree of treatment.

3.4 Current Disposal Practices

Selected information for typical land application projects in Canada is presented in Appendix C.

3.4.1 Treated Municipal Wastewater. As of January 1983, land application of treated municipal wastewater was practised in 79 municipalities in Canada (Table 3). Sixty-nine of them were located in the semi-arid regions of Saskatchewan, Alberta and British Columbia.

3.4.2 Treated Municipal Sludge. As of January 1983, land application of treated sludge was practised in 141 municipalities in Canada (Table 3). One hundred and twenty-nine of them were located in Ontario, Alberta and British Columbia.

TABLE 2 TYPICAL PROPERTIES OF ANAEROBICALLY DIGESTED SLUDGE (Schmidtke, 1981)

Constituent	Units	Primary Plants* Range	Primary Plants* Mean	Secondary Plants** Range	Secondary Plants** Mean
Total Solids	TS %	2.8 - 12.5	8.8	2.0 - 12	4.1
Volatile Solids	VS %	24 - 61	43.4	36 - 70	51
Ammonium Nitrogen	mg/L	100 - 590	326	250 - 1 200	628
Total Kjeldahl Nitrogen	mg/L	950 - 2900	1 736	1600 - 3000	2114
Total Phosphorus	mg/L	240 - 2600	713	390 - 2900	975
Zinc	mg/L	2.8 - 130	74.3	4 - 225	55.5
Copper	mg/l	4.6 - 150	54.5	7 - 148	34.8
Nickel	mg/L	0.7 - 15	4.4	0.26 - 16.8	6.5
Chromium	mg/L	2 - 68	16.5	2 - 430	41.6
Lead	mg/L	11 - 86	40.9	3.7 - 60	21.8
Cadmium	mg/L	0.2 - 2.6	0.7	0.1 - 8.7	1.4
Cobalt	mg/L	< 0.6 - 1.4	1.0	0.3 - 3.6	0.8

* Number of Plants = 10.

** Number of Plants = 30.

TABLE 3 LAND APPLICATION SITES FOR TREATED MUNICIPAL WASTEWATER AND SLUDGE IN CANADA*

	Number of Sites	
Province	Wastewater	Sludge
Yukon	0	0
Northwest Territories	1	0
British Columbia	31	44
Alberta	26	20
Saskatchewan	12	0
Manitoba	4	1
Ontario	3 (+20 industrial)	65
Quebec	1	0
Nova Scotia	0	8
New Brunswick	-	-
Prince Edward Island	0	3
Newfoundland	1	0
Totals	79	141

* Limited to data available January 1983. Sites are defined as municipalities using land application.

4 SOIL CONSIDERATIONS

4.1 Introduction

Waste materials added to soil may be modified by physical filtration, inorganic and organic chemical reactions, and biological transformations. This section introduces the physical, chemical and biological properties of soil that are important for the design and management of land application systems. More information can be obtained from soil textbooks.

The Canadian System of Soil Classification (1978) defines soil as "naturally occurring unconsolidated mineral or organic material at least 10 cm deep that occurs at the earth's surface and is capable of supporting plant growth". It consists of horizons of weathered material overlying unconsolidated and more or less weathered parent material from which the profile has developed.

The importance of understanding soil processes in order to avoid mismanagement of land application systems cannot be overemphasized. The effects of poor management can be the degradation of local soil and water resources leading to costly reclamation, long recovery periods and decreased productivity of the resources. In general, good agronomic practices result in effective, well-managed waste treatment.

4.2 Physical Properties and Processes

The physical aspects of waste treatment through land application systems involve the processes of filtration and dilution. As wastewater moves through soil, suspended solids are removed by filtration and the filtrate may be diluted with soil water. The rate of these processes is affected by the soil's physical properties.

4.2.1 **Soil Composition.** Soil is composed of mineral matter, organic matter, water containing dissolved substances (i.e., solution), and air. The approximate proportions of these components in the plow layer of a typical agricultural soil are shown in Figure 6. Solid matter and pore space occupy about equal volumes. Generally, about 50% of the pore space is occupied by solution, unless the soil is very wet or very dry. Organic matter comprises from 1 to 10% of the solid fraction, with the remainder being mineral particles of varying sizes: sand, 0.05-2.0 mm; silt, 0.002-0.05 mm; and clay, <0.002 mm.

4.2.2 **Soil Texture.** Soil texture is defined by the proportions of sand, silt and clay in soil as illustrated in Figure 7. Texture, in combination with other physical properties

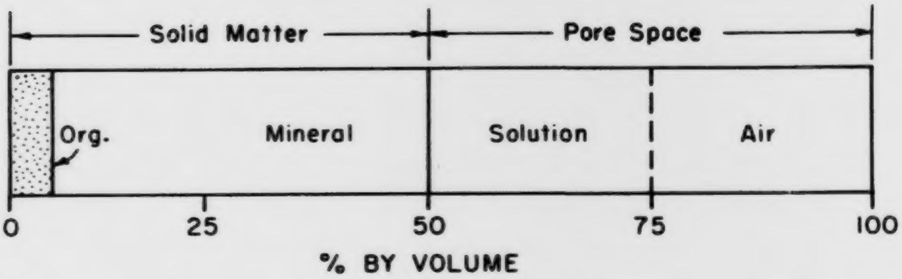


FIGURE 6 VOLUME COMPOSITION OF AN AGRICULTURAL SURFACE SOIL (15-20 cm in depth) REPRESENTING FAVORABLE CONDITIONS FOR PLANT GROWTH

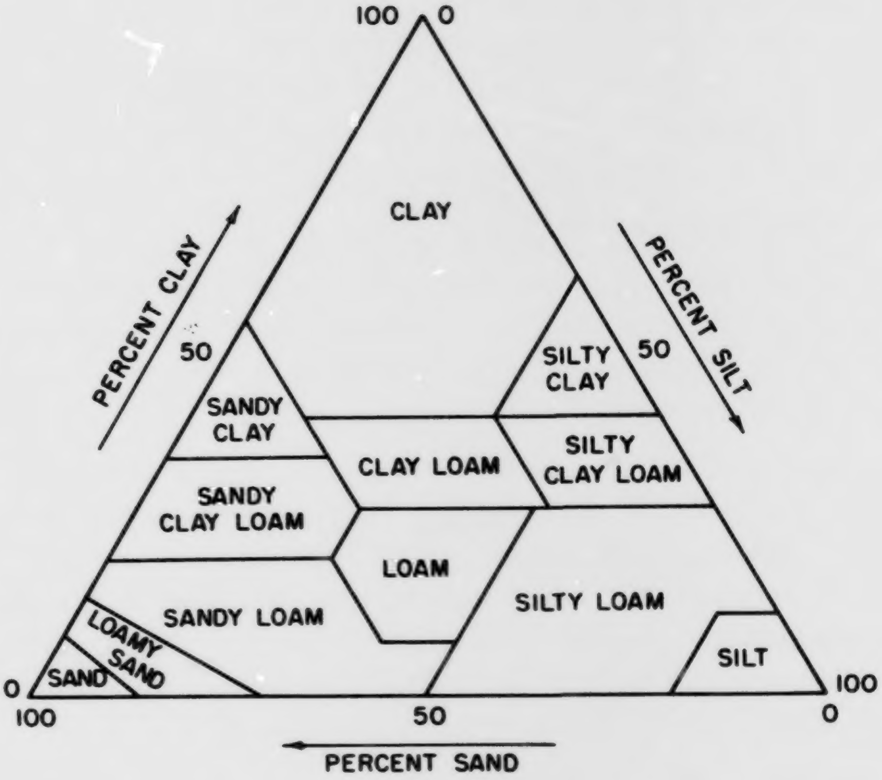

100
0
CLAY
PERCENT CLAY
PERCENT SILT
50
SILTY CLAY
50
SANDY CLAY
CLAY LOAM
SILTY CLAY LOAM
SANDY CLAY LOAM
LOAM
SANDY LOAM
SILTY LOAM
LOAMY SAND
SAND
SILT
0
100
100
50
0
PERCENT SAND

FIGURE 7 PERCENTAGES OF SAND, SILT AND CLAY IN SOIL TEXTURAL CLASSES

affects the water movement and retention properties of soils. It also influences chemical processes such as solute sorption. In general, water movement is slower and water retention and solute sorption are greater in fine-textured than in coarse-textured soils.

4.2.3 **Soil Structure.** Soil structure refers to the arrangement of sand, silt and clay in combination with organic matter into definable secondary structures called aggregates. Some common soil structures and their effects on water infiltration are illustrated in Figure 8. Aggregate stability is favoured by increasing amounts of organic matter and inorganic cementing agents such as iron and aluminum oxides and calcium carbonate. Granular structure is generally found only in the top 25 cm of soil and can be maintained or destroyed by agricultural practices, whereas blocky and prismatic aggregates occur well below the soil surface and are less affected by agricultural practices. Aggregate breakdown is undesirable because it generally results in impeded water and air movement.

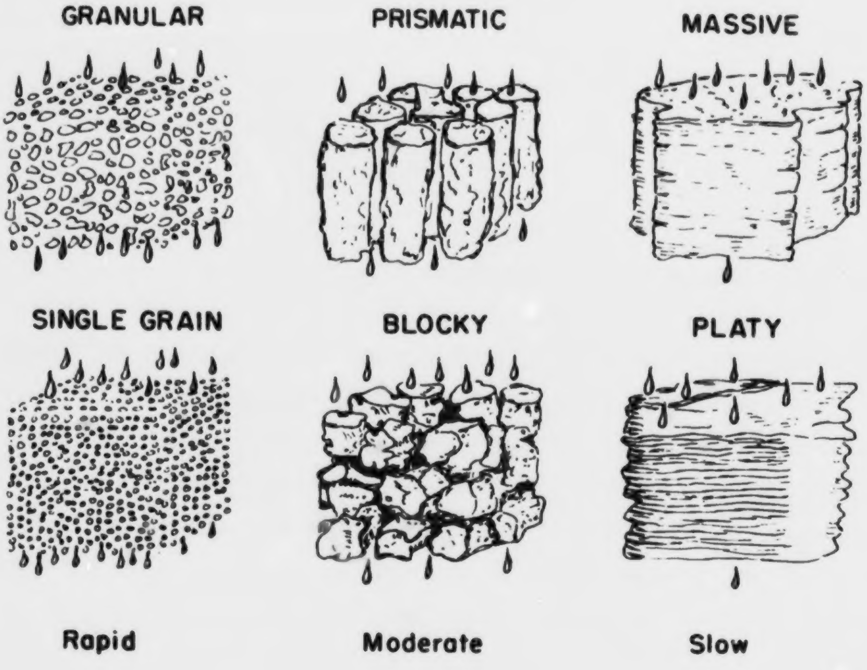


FIGURE 8 SOIL STRUCTURES AND THEIR RELATIONSHIP TO INFILTRATION RATE (U.S. Dept. of Interior and U.S.D.A., 1959)

4.2.4 **Infiltration and Permeability.** Infiltration is the process of water entry into the soil, through the soil surface and vertically downward. The process is of great practical significance because it determines the rate at which liquid wastes can be applied to the soil. The infiltration rate is influenced by the permeability and moisture content of the soil. Permeability refers to the ease with which water and air pass through soil. It may be quantified in terms of the rate of water movement through a unit cross-section of saturated soil in a given time, according to Table 4. In general, permeability decreases with increasing clay content of soil; however, it is also related to structure as illustrated in Figure 8.

TABLE 4 PERMEABILITY CLASSES FOR SATURATED SOIL (U.S. D.A. Soil Conservation Service, 1971)

Soil Permeability(cm/h)	Class	Textural Class* Probable
<0.02	very slow	Dense, compacted clay
0.02 - 0.1	slow	Clay, loam, clay
0.1 - 0.3	moderately slow	Clay loam to loam
0.3 - 1.0	moderate	Loam to sandy loam
1.0 - 3.0	moderately rapid	Loamy sand to sand
3.0 - 10	rapid	Coarse sand
more than 10	very rapid	Gravel

* May vary in individual cases because of differences in soil structure.

4.2.5 **Water Retention.** Soil water is characterized by the energy with which it is retained. A common term used to describe this energy is "soil moisture tension". Under field conditions, tension is exerted on soil moisture through 1) natural drainage, 2) evaporation, and 3) plant use. The soil moisture characteristic curve (Figure 9) illustrates a sequence of events as a wet soil is allowed to drain freely. As the drainage water leaves the soil surface, relatively low tensions are developed and the large pores, which hold water at low tensions, empty first. The smaller pores hold water with greater tension and are able to retain water against gravitational forces. The moisture content of soil after being saturated and allowed to drain for 48 h is referred to as field capacity. A portion of this moisture is extractable by plant roots while another portion is held too tightly. The threshold between plant available and plant unavailable water is termed the wilting point. For diagnostic purposes, field capacity is considered to be the water content of soil at 33 kPa moisture tension and the permanent wilting point the water content at 1 500 kPa tension. Plant-available water is the difference in the amounts of water held at field

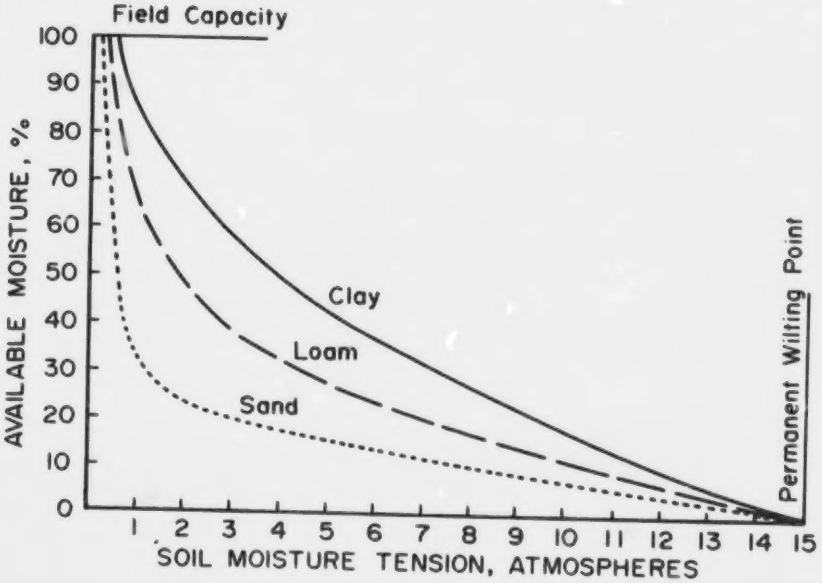


FIGURE 9 TYPICAL MOISTURE CHARACTERISTIC CURVES FOR CLAY, LOAM AND SANDY SOILS (USDA, Soil Conservation Service, 1971)

capacity and at the permanent wilting point and is a measure of the storage capacity of the soil for water (Figure 10). Moreover, it defines the amount of wastewater that can be applied to a dry soil without direct drainage to the groundwater. The available water capacity for sandy soils is relatively low (3 to 9% on a soil dry weight basis), and increases as soil particle size decreases, reaching a maximum about 12% for a silt loam soil. Available water capacities greater than 15 cm in the surface 120 cm of soil are desirable to provide sufficient retention time for wastewater renovation.

4.2.6 **Water Movement in Soil.** In relatively dry soil, much pore space is filled with air and as water enters the soil by infiltration, the pore space is rapidly filled. With continued application of water the infiltration rate gradually decreases, and approaches a constant value at approximately the permeability of the least permeable soil layer. Continued application in excess of the limiting infiltration rate will result in surface ponding and runoff. An exception often occurs on slopes where excess water may move laterally along the face of the least permeable layer and emerge at the slope base some distance from the original point of application as in a saline seep. Infiltration rate thus depends on the permeability within the profile, and on topography.

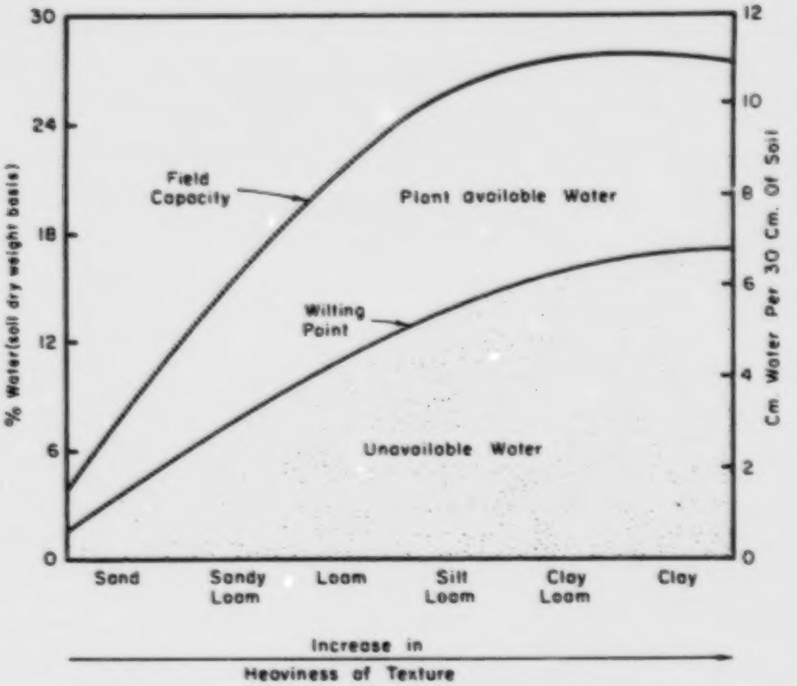


FIGURE 10 RELATIONSHIP BETWEEN SOIL MOISTURE CHARACTERISTICS AND SOIL TEXTURE

A thin layer with low permeability may form at the soil surface if the infiltrating liquid contains fine particles which are screened out at the surface. Permeability can also be reduced by applying water in a manner which disturbs the soil surface, breaking down aggregates and dispersing the soil particles. Field experience has shown that when surface clogging occurs, the problem is reduced by allowing the soils to dry for several days.

Infiltration in northern soils can be affected by low temperatures resulting in head losses due to increased viscosity. In land application systems, this factor is generally ignored.

4.3 Soil Chemical Properties and Processes

Chemical reactions between dissolved ions and compounds within the soil alter the mobility and determine the fate of waste constitutents. Many of these reactions, such as adsorption, precipitation and cation exchange, depend on the surface chemistry of the colloid-sized (<0.002 mm) particles in soil. The inorganic colloidal fraction includes the clay minerals (layer silicates) and oxides and hydrous oxides of iron, manganese and aluminum. The organic colloidal fraction is composed mainly of humic materials which are brown to dark brown non-crystalline substances modified from original tissues or synthesized by soil organisms. The soil solid phase components usually exist in combination. For example, organic matter and minerals may occur as organo-mineral complexes, iron, aluminum and manganese oxides may coat the surfaces of clay minerals, and clay minerals may coat the surfaces of the larger inorganic components such as sand and silt particles.

From a wastewater renovation point of view, perhaps the most important chemical reactions are adsorption and precipitation. Both of these reactions result in the removal of dissolved substances from solution.

4.3.1 **Adsorption**. Adsorption, sometimes referred to as sorption, is a general term referring to uptake and surface accumulation of material from a fluid by a solid. For convenience, adsorption can be grouped into ion-exchange, specific adsorption and physical adsorption. When the adsorption of one or more ionic species is accompanied by the simultaneous desorption of an equivalent amount of other ionic species, the process is called ion exchange. In soils, both cation and anion exchange are possible. However, in Canadian soils anion exchange is negligible because the soil particles are predominantly negatively charged. Anion exchange will not be discussed here.

Cations retained on negatively charged soil particles by weak forces are termed exchangeable and the amount of these cations is termed the cation exchange capacity of the soil. Cation exchange capacity and the amount of individual exchangeable cations are usually expressed in milligram equivalents (meq) per 100 g of soil. The cation exchange capacity of mineral soils ranges from about 5 to 50 and is greater in organic soils. The adsorbed cations interchange with cations in the soil solution according to the Law of Mass Action. For example:

$$CaX_2 + 2\,Na^+ = 2\,NaX + Ca^{2+}$$

where X denotes a cation exchange site.

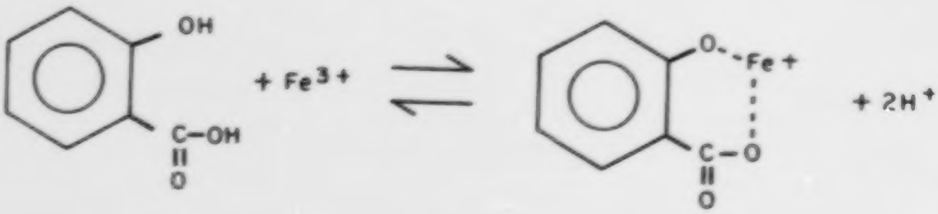
Specific adsorption, also called chemisorption, results from surface complex formation and strong electrostatic forces. It occurs on the surfaces of hydrous iron, aluminum and manganese oxides, and in association with hydroxyl groups on the exposed edges of clay minerals and functional groups of soil organic matter. Specifically adsorbed ions are not easily desorbed, except by ions of a greater affinity, or by altering the surface chemistry (e.g., by changing pH). The great affinity of soils for phosphate and heavy metals is the result of specific adsorption. Specific adsorption is a particularly effective wastewater renovation process.

Physical adsorption involves the attachment of adsorbent and adsorbate through short-range and weak atomic and molecular interaction forces (van der Waal's forces) which operate when electron clouds of the atoms do not overlap sufficiently to cause strong attractive electrostatic forces. Desorption is thus easily facilitated. Such forces operate in all adsorbent-adsorbate relationships, but appear to be the principal forces of adsorption for nonionic nonpolar molecules (e.g., DDT). Soil organic matter contains surfaces that are said to be hydrophobic (i.e., "water-repelling"). Water molecules compete poorly with nonpolar molecules for these sites. Consequently, nonpolar molecules such as aldrin, and chlorinated hydrocarbons show strong adsorptive behaviour in soils rich in organic matter. Nonionic polar molecules can also be adsorbed by hydrogen bonding. Soil functional groups capable of hydrogen bonding include oxygen atoms on silicate mineral surfaces, edge hydroxyls, and carboxyl, hydroxyl and amino groups of organic matter.

4.3.2 **Chemical Precipitation.** Chemical precipitation refers to the formation of a solid that is sparingly soluble in the medium in which it was formed. Although precipitation is theoretically quite distinct from adsorption, in practice it is not easy to distinguish between the two processes in soils. For example, phosphate adsortion on calcium carbonate can lead to the formation of sparingly soluble calcium phosphate. Precipitation occurs when the product of ions in solution exceeds the solubility product of a sparingly soluble compound. Conversely, dissolution occurs when the ion product in solution is less than the solubility product. In this way, sparingly soluble solids tend to buffer the concentration of ions in the soil solution. Studies in Ontario have shown that phosphate is precipitated as octacalcium phosphate in soils amended with lime-treated sewage sludge. It is believed that trace metals and phosphate ions coprecipitate to some extent with iron, aluminum and manganese hydrous oxides in soils.

The solubility of some soil precipitates or minerals is influenced by their oxidation status. When soils become waterlogged and anaerobic, Fe^{3+} is reduced to Fe^{2+} and Mn^{4+} to Mn^{2+}. The lower oxidation states of the metals are more soluble than the higher oxidation states. Thus, iron and manganese oxides are dissolved, releasing previously sorbed or coprecipitated species such as metals and phosphate into solution.

4.3.3 **Complex Formation.** Complex formation is a chemical reaction involving the combination of cations with molecules or anions containing free pairs of electrons and can be either electrostatic or covalent. Chelation occurs when more than one bond is formed between a cation and the functional groups of the complexing agent. It results in the formation of a ring structure incorporating the metal ion as depicted in the following diagram.



The resulting complex is called a chelate. Chelate stability increases with increasing numbers of ring structures; however, this does not imply anything about solubility. It is useful to categorize metal chelates in soils in terms of solubility because solubility determines metal mobility and plant availability. Three principal categories have been proposed (Hodgson, 1963), although the complexity of soil systems results in considerable overlap between categories. These include i) the relatively high molecular weight humic substances which have a high affinity for polyvalent metals but are largely insoluble in soil; ii) low molecular weight organic acids and bases (e.g., citric, malic and amino acids) which have high solubility in association with metals; and iii) soluble ligands (e.g., certain fractions of soil humus) which precipitate on reaction with polyvalent metal ions. It is thought that the formation of soluble chelates may increase heavy metal mobility and reduce the capacity of soil to strongly retain these constituents by specific adsorption and precipitation.

4.4 Biological Properties and Reactions in Soil

Only a small part, perhaps 0.1 to 4%, of the organic material in soil is living tissue. A large part consists of the modified remains of plant and microbial cells. However, the living tissue (i.e., biological population) of a soil is a very important part of the organic fraction. It consists of a microflora, including bacteria, viruses, actinomycetes, fungi and algae; and an animal population comprising protozoa, nematodes, segmented worms and arthropods. The approximate numbers of organisms, excluding segmented worms, commonly found in soils are presented in Table 5.

Although fungi are greatly outnumbered by bacteria and actinomycetes in soil, their extensive mycelial growth constitutes a large mass of tissue. Direct observation

TABLE 5 APPROXIMATE NUMBERS OF ORGANISMS COMMONLY FOUND IN SURFACE SOILS* (Martin and Focht, 1977)

Organism	Estimated numbers/g
Bacteria	3 000 000 to 500 000 000
Actinomycetes	1 000 000 to 20 000 000
Fungi	5 000 to 900 000
Yeasts	1 000 to 100 000
Algae	1 000 to 500 000
Protozoa	1 000 to 500 000
Nematodes	50 to 200

* The figures for bacteria, actinomycetes, fungi, and yeasts are based on plate counts and refer to viable propogules grown on the plating media. In addition to these there are large numbers of slime molds (Myxomycetes), viruses or phages of bacteria, algae, fungi, insects, plants, arthropods, earthworms, mycoplasmas, and other organisms.

and physiological methods have indicated that in most agricultural soils fungi represent about 75% and bacteria plus actinomycetes about 25% of the total microbial biomass (Anderson and Domsch, 1978). The biological population in soil changes continuously with changing environmental conditions. Only a fraction of the total population is actively growing and involved in organic matter decomposition and nutrient transformations at any given time. The remainder are in a passive or resting stage waiting for conditions to change.

Microorganisms are most numerous and metabolically active within a few centimetres of the soil surface where environmental conditions change frequently and drastically. Below the plough layer numbers and activity decrease rapidly with depth and become insignificant.

Most biological reactions involve decomposition of organic materials in soil. Decomposition can be considered to be a team effort among many different organisms. Decomposition of newly added organic material may be envisioned as taking place in three general steps. In the initial stage, lasting a few weeks, organisms attack the more easily decomposable material. Oxygen is consumed and water and CO_2 are released, and there is a rapid buildup of microbial tissue or biomass. In the second stage, the numbers of organisms decline as the easily degradable organic fraction is exhausted. The resulting mass of dead microbial tissue, intermediate decay products and more resistant compounds from the original organic material, are partially degraded to humic substances. In the final stage, the soil microorganisms decline to about the same level as before the addition of fresh organic material. The humic substances are degraded slowly by highly specialized organisms at a rate of 2 to 5% per year depending upon environmental conditions. The organic matter cycle in soil is illustrated in Figure 11.

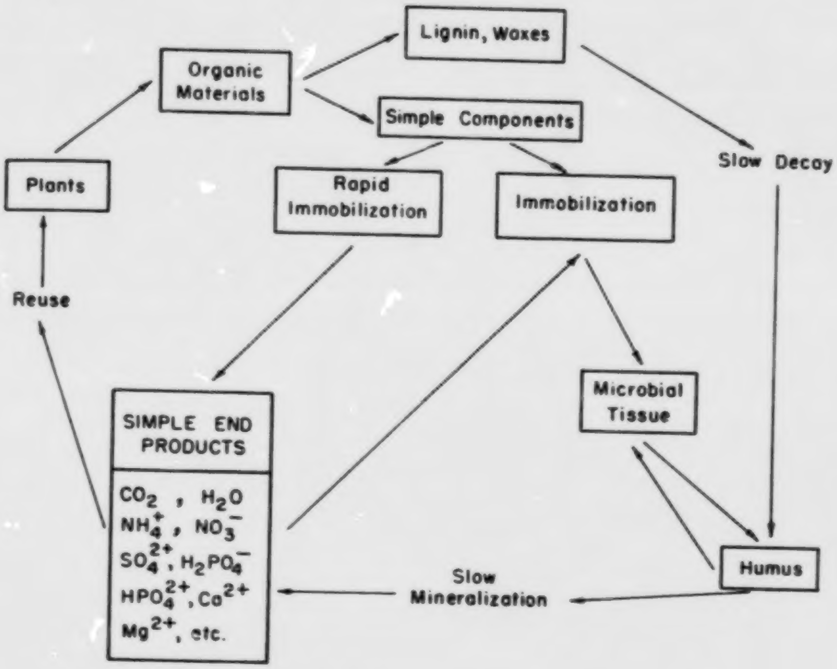

Lignin, Waxes
Organic Materials
Simple Components
Slow Decay
Plants
Rapid Immobilization
Immobilization
Reuse
Microbial Tissue
SIMPLE END PRODUCTS
CO_2 , H_2O
NH_4^+ , NO_3^-
SO_4^{2+} , $H_2PO_4^-$
HPO_4^{2+} , Ca^{2+}
Mg^{2+}, etc.
Humus
Slow Mineralization

FIGURE 11 ORGANIC MATTER CYCLE IN SOILS

In natural systems that receive localized or periodic additions of organic matter, these three stages may overlap with several processes occurring simultaneously. In the winter months little decomposition occurs as the biological activity declines when temperatures are low. In the temperature range 5 to 30°C, soil biological reaction rates generally double for each 10°C rise in temperature.

The bacteria, actinomycetes and fungi are the most abundant soil microorganisms. They all take part in organic matter decomposition in soil. The majority of soil bacteria are heterotrophic and require organic compounds for their energy and carbon needs. Most organic compounds that are added to soil or produced in soil are decomposed by heterotrophic bacteria. Only a few bacteria are autotrophic and obtain energy from transformations of inorganic compounds and carbon from CO_2. However, nitrifying bacteria, which oxidize ammonium to nitrate, are autotrophic and are very important both agronomically and environmentally.

Strictly aerobic and anaerobic bacteria are found in soil, in addition to bacteria capable of developing in both the presence and absence of oxygen. Most grow best under neutral to slightly alkaline conditions. At pH values of 5.5 to 5 the numbers begin to decline and below pH 4, numbers and activity decline sharply. Actinomycetes are aerobic, heterotrophic microorganisms primarily involved in humus decomposition. Their growth is restricted by soil acidity and very few grow below pH 5. All fungi are heterotrophic and most are aerobic and grow best in near neutral soils. However, some are adapted to low pH and become dominant in acid soils.

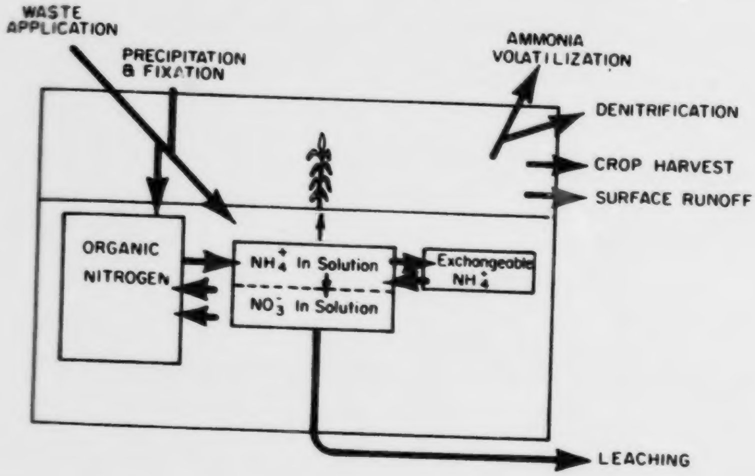
The rate at which organic matter decomposes and end products are formed depends on the aeration status and temperature of the soil. Under aerobic conditions, up to 60% of the organic carbon may be respired by organisms as carbon dioxide in the initial stage of decomposition. Much of the remaining carbon is incorporated into microbial cells and some of this is subsequently respired when the population declines. Under anaerobic conditions, decomposition is generally much slower and the end products are different. Some CO_2 and methane (CH_4) are produced; however, most of the carbon, perhaps 70%, remains partially degraded as organic acids and alcohols. Since relatively few organisms can degrade these products in the absence of oxygen, they accumulate. Under aerobic conditions, organic nitrogen and ammonia are transformed to nitrate, and organic sulphur to sulphate, whereas under anaerobic conditions, ammonia, nitrous oxide, nitrogen gas and hydrogen sulphide are formed. Foul odours are often associated with anaerobic decomposition of organics, particularly if their nitrogen and sulphur contents are high.

The organisms involved in decomposition processes require nutrient elements just as do higher plants and animals. If the amounts in the organic residues added to soil are low, nutrients must be obtained from the soil or from fertilizer; otherwise decomposition will be delayed. The carbon to nitrogen ratio of the residue is especially important. If it is greater than 25, initial decomposition will be slow due to nitrogen deficiency.

4.5 Fate of Some Waste Constituents in Soil

In this section, the fate of some constituents added to soil in treated wastewater and in sludge are briefly examined. They include nitrogen, phosphorus, heavy metals and boron.

4.5.1 Nitrogen. Municipal wastewaters and sludges contain variable amounts of organic, nitrate (NO_3^-), nitrite (NO_2^-) and/or ammonium (NH_4^+) nitrogen (N). The fate of nitrogen in soil is illustrated in Figure 12. The main steps in nitrogen transformation in soil are mineralization, immobilization, nitrification, denitrification, ammonia volatilization and leaching.



WASTE APPLICATION
PRECIPITATION & FIXATION
AMMONIA VOLATILIZATION
DENITRIFICATION
CROP HARVEST
SURFACE RUNOFF
ORGANIC NITROGEN
NH_4^+ In Solution
NO_3^- In Solution
Exchangeable NH_4^+
LEACHING

FIGURE 12 FATE OF NITROGEN IN SOILS

Mineralization is the conversion of organic nitrogen to inorganic forms by microbial decomposition.

Immobilization occurs when inorganic nitrogen in the form of NH_4^+ or NO_3^- is taken up by soil organisms to satisfy their nitrogen requirements. Immobilized nitrogen is released when the organisms die. When residues with a high C/N ratio (i.e., >25) are decomposed, there is little initial mineralization because most of the nitrogen is immobilized by the microorganisms.

Nitrification refers to the microbial conversion of NH_4^+-N to NO_3^--N. Two specific groups of nitrifying bacteria are Nitrosomonas sp. and Nitrobacter sp. The conversion of NH_4^+ by Nitrosomonas sp. is:

$$2\ NH_4^+ + 3\ O_2 \rightarrow 2\ NO_2^- + 4\ H^+ + 2\ H_2O + \text{energy.}$$

The conversion by Nitrobacter sp. is given by:

$2\ NO_2 + O_2 \rightarrow 2\ NO_3^- + \text{energy}.$

The transformation from NO_2^- to NO_3^- is very rapid so that little NO_2^- accumulates in soil and the net result is accumulation of NO_3^-. The optimum pH for nitrification is slightly above 7.

Denitrification results in the loss of nitrogen in gaseous form from the soil system, and occurs under anaerobic conditions when nitrate and readily degradable carbon sources are available. The pathway is $NO_3^- \rightarrow NO_2^- \rightarrow N_2O \rightarrow N_2$. Denitrification may be caused by certain groups of bacteria and by chemical reduction, in which case the process is called chemo-denitrification.

Nitrogen may be lost as ammonia (NH_3) gas from moist alkaline soils. When liquid sewage sludge is applied to the soil surface, 50% or more of NH_4^+-N may be lost by volatilization depending on the application rate and soil properties. In general, losses increase with increasing air movement, soil temperature and pH, and decreasing clay content of soil.

Leaching refers to the downward movement of water through soil. Because of rapid nitrification, NH_4^+-N generally constitutes only a small portion of the available inorganic nitrogen in soil. The predominant form tends to be NO_3^- which is very soluble in water and is not adsorbed by soil. As water infiltrates into soil, NO_3^- will be transported and, if not absorbed by plant roots, may be lost to the groundwater. To minimize NO_3^- losses, nitrogen input to soil should not exceed the sum of the crop requirement and losses due to denitrification and volatilization.

4.5.2 **Phosphorus.** Phosphorus, like nitrogen, is an essential nutrient for plant and animal growth. Both are major contributors to eutrophication of surface waters; however, they behave very differently in soil. Phosphorus is not lost from the soil by volatilization and only minor amounts are lost by leaching. The $H_2PO_4^-$ and HPO_4^{2-} ions in soil are specifically adsorbed or precipitated as sparingly soluble iron, aluminum and calcium phosphates (Hwang et al., 1976). The fate of phosphorus added to soils at typical loading rates is depicted in Figure 13.

Adsorption seems to be the immediate mechanism of phosphate binding in soil (de Haan and Zwerman, 1976). Subsequently precipitation occurs and the adsorption sites become available for further binding. This mechanism of alternate adsorption and precipitation greatly enhances the total phosphate fixation capacities of soil (Beek and de Haan, 1974).

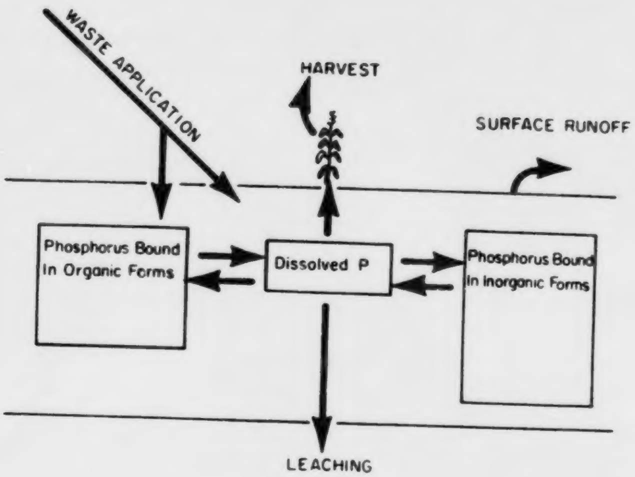

WASTE APPLICATION
HARVEST
SURFACE RUNOFF
Phosphorus Bound In Organic Forms
Dissolved P
Phosphorus Bound In Inorganic Forms
LEACHING

FIGURE 13 FATE OF PHOSPHORUS IN SOILS

The Langmuir equation has been used to relate phosphate concentrations in solution to phosphates adsorbed onto soil components, and to calculate the phosphorus adsorption capacities of various soils (Olsen and Watanabe, 1957; Syers, et al., 1973; Tofflemire, 1976). The phosphorus adsorption capacities of six Alberta soils are presented in Table 6.

Assuming a wastewater with a maximum phosphorus concentration of 10 mg/L is applied at a maximum rate of 40 cm/annum, the expected lifetime for wastewater disposal with no crop growth ranges from 76 years for the Carmangay loamy sand to 53 years for the Seven Persons sandy clay loam. However, cropping these soils would extend the design life almost indefinitely because of phosphorus uptake during crop growth.

Phosphorus in soils may be organic or inorganic. Inositol phosphates are believed to a major form of organic P. Inorganic phosphates may be present as orthophosphate, the predominant form, or polyphosphates which are hydrolysed to orthophosphate. Biological activity can convert organic P to inorganic P and vice-versa. Phosphate ions do not remain in soil solution to any significant extent, but are either adsorbed or precipitated. Heavy applications of sewage sludge to neutral soils in Ontario over six years resulted in phosphate concentrations in the soil solution of ≤ 0.9 mg P/L. Although the dissolved phosphorus concentration in soil solution is low, the plant requirement is met by desorption of adsorbed phosphate or dissolution of precipitated phosphate.

TABLE 6 PHOSPHORUS ADSORPTION CAPACITIES OF SIX ALBERTA SOILS (Lutwick and Graveland, 1982)

Soil	Sampling Depth (cm)	Phosphorus Adsorption Capacity (mg P/100 g)
Cavendish (SL)*	0 - 12	22.2
	12 - 40	14.7
	40 - 58	6.3
	58 - 120	28.2
Maleb (SL)	0 - 7	18.0
	7 - 26	11.9
	26 - 45	23.8
	45 - 70	36.5
	70 - 110	32.8
Seven Persons (SCL)	0 - 10	-21.7**
	10 - 31	31.1
	31 - 46	31.7
	46 - 78	23.6
	78 - 95	30.4
	120 - 150	95.0
Carmangay (LS)	0 - 21	15.9
	21 - 30	14.8
	30 - 49	17.5
	49 - 100	30.1
Granum (SL)	0 - 12	16.6
	12 - 27	21.9
	27 - 45	38.2
	45 - 100	32.8
Coaldale (SC)	0 - 21	42.1
	21 - 28	40.1
	28 - 33	41.6
	33 - 70	40.2
	70 - 110	38.1

* S-sand, L-loam, C-clay, e.g., SCL - sandy clay loam.

** The soil released P to the solution (i.e., P desorption occurred).

4.5.3 **Heavy Metals.** The fate of heavy metals added to soil is summarized in Figure 14. Several processes in soils previously discussed remove metals from solution: the formation of insoluble complexes, precipitation as insoluble minerals and adsorption (cation exchange and specific adsorption). Soluble organo-metallic complexes and chelates retain a fraction of the metals in a water-soluble form. A process called

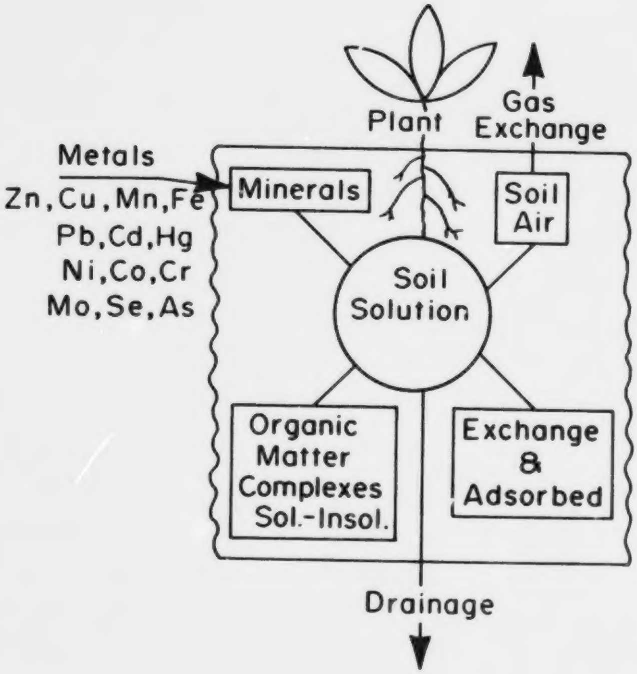

Plant
Gas Exchange
Metals
Zn, Cu, Mn, Fe
Pb, Cd, Hg
Ni, Co, Cr
Mo, Se, As
Minerals
Soil Air
Soil Solution
Organic Matter Complexes Sol.-Insol.
Exchange & Adsorbed
Drainage

FIGURE 14 FATE OF HEAVY METALS IN SOILS (Lindsay, 1979)

reversion has been observed in the reaction of some metals with soil. In this process, the metal is though to be converted slowly to forms that are less soluble and extractable. The actual mechanism of reversion is not clearly understood.

Heavy metals tend to be strongly retained by soil; estimates of the residence time range from 300 to 3000 years (Bowen, 1975). Bates et al. (1975) estimated that it would take approximately 1000 cropping cycles to remove all the cadmium added in one heavy sludge application (about four times the recommended annual application rate for Ontario). Leaching of metals is not likely to be a problem except when soils are allowed to become anaerobic and then are drained rapidly. The reducing conditions in anaerobic soil increase metal solubility and mobility by dissolution of iron and manganese oxides and the formation of soluble organo-metallic complexes.

The selectivity of hydrous iron and aluminum oxides for divalent metal cations increases in the order: Cd < Ni < Zn < Cu < Pb (Kinniburg et al., 1976). Sorption by humic acid, a high molecular weight fraction of soil organic matter at pH 5.8 follows the order:

Ni < Zn < Cd < Cu (Kerndorf and Schnitzer, 1980). The implication is that metals such as cadmium and nickel are less strongly retained by soil and tend to be more mobile than copper.

Metals such as mercury and selenium may form volatile alkyl compounds in poorly drained soils through microbial processes and escape to the atmosphere.

4.5.4 **Boron.** Boron is an essential plant nutrient whose concentration in the range between deficiency and toxicity is quite narrow for many crops, often only a few mg/L. Irrigation with high boron sewage effluents may cause crop injury. Boron may be adsorbed by soil colloids; however, within the pH range of agricultural soils, adsorption is weak and removal occurs by leaching.

5 ENVIRONMENTAL HEALTH CONSIDERATIONS

5.1 Introduction

Land application of treated municipal wastewater (effluent) and sludge presents the opportunity to recycle resources and to avoid adverse environmental impacts which may be associated with conventional disposal practices. Land application of treated wastewater provides water and nutrients for crop growth and avoids nutrient overloading and eutrophication of natural water bodies. Land application of sludge provides nutrients for crop growth and organic matter for soil conditioning, and avoids potential water pollution problems resulting from landfilling or ocean dumping, and air pollution problems resulting from incineration; furthermore, it is usually the most economic means of sludge disposal.

However, land application involves risks, because sludge may contain metals and industrial organic compounds, and wastewater and sludge may contain pathogens at detrimental concentrations. In this section, the risks presented by land application of effluent and sludge are assessed and strategies that have been recommended to minimize the risks are discussed.

5.2 Inorganic Chemical Contaminants

The inorganic contaminants of main concern in treated municipal wastewater and sludge are toxic meals because they present risks to crop production and animal and human health. They enter sewage treatment facilities in various chemical forms, both soluble and insoluble. Sewage treatment partitions the metals into the sludge and usually reduces the concentrations in the effluent to below the maximum acceptable levels (see Appendix B). For this reason, most of the following discussion relates to land application of sludge.

Chaney (1982) compiled data showing the concentrations of metals in plants that can be considered "normal" and those that cause toxicity (Table 7). Where indicated, the soil-plant barrier prevents uptake and/or transport in the plant, preventing major accumulation in the food chain. Chaney also compares these data with the maximum levels of metals chronically tolerated in feed for cattle, sheep, swine and chickens. This information is useful in comparing the relative toxicities of metals to plants and animals, but it may not apply directly to sludge-fertilized crops or to ingestion of sludge or soil because of metal interactions in the plants and animals (National Research Council, 1980).

TABLE 7 MAXIMUM TOLERABLE LEVELS OF DIETARY MINERALS FOR DOMESTIC LIVESTOCK IN COMPARISON WITH LEVELS IN FORAGES (Chaney, 1982)

Element	"Soil Plant Barrier"	Level in Plant Foliage* (mg/kg dry foliage)		Maximum Level Chronically Tolerated (mg/kg dry diet)			
		Normal	Phytotoxic	Cattle	Sheep	Swine	Chicken
As, inorganic	yes	0.01 - 1	3 - 10	50	50	50	50
B	yes	7 - 7.5	75	150	(150)	(150)	(150)
Cd**	Fails	0.01 - 1	5 - 700	0.5	0.5	0.5	0.5
Cr^{3+}, oxides	yes	0.1 - 1	20	(3 000)	(3 000)	(3 000)	3 000
Co	Fails?	0.01 - 0.3	25 - 100	10	10	10	10
Cu	yes	3 - 20	25 - 40	100	25	250	300
F	yes?	1 - 5	-	40	60	150	200
Fe	yes	30 - 300	-	1 000	500	3 000	1 000
Mn	?	15 - 150	400 - 2 000	1 000	1 000	400	2 000
Mo	Fails	0.1 - 3.0	100 10	10	20	100	
Ni	yes	0.1 - 5	50 - 100	50	(50)	(100)	(300)
Pb**	yes	2 - 5	-	30	30	30	30
Se	Fails	0.1 - 2	100 (2)	(2)	2	2	
V	yes?	0.1 - 1	10	50	50	(10)	10
Zn	yes	15 - 150	500 - 1 500	500	300	1 000	1 000

* Continuous long-term feeding of minerals at the maximum tolerable levels may have adverse effects. Interactions between metals were not studied and may increase tolerance above the values shown where diets contain increased concentrations of more than one metal. Concentrations in parentheses were not available for the species listed and were extrapolated from data for similar species.

** Maximum tolerable dietary concentrations based on residues in animal products used as human food rather than on toxicities to the species listed.

National and provincial guidelines and regulations for the land application of sludge have recognized that metals in sludge must be limited to prevent toxicity problems (Table 8). Although the values may have been derived from different criteria, there is general agreement that levels of cadmium, zinc, copper, lead, chromium and mercury must be limited. Furthermore, most jurisdictions have prescribed maximum cumulative loadings of these elements to agricultural lands (Table 9). It is in this area that the jurisdictions have taken different approaches, with Norway and Sweden, for example, prescribing very low cumulative loadings.

The metals commonly present in treated wastewater and sludge have been classified as those which are likely to pose little hazard for land application and those which pose a significant hazard (CAST, 1976). The metals posing little hazard include manganese, iron, aluminum, chromium, arsenic, selenium, antimony, mercury, and lead. Of these, manganese, iron and aluminum occur in large amounts in natural soils and are only slightly soluble in well-aerated soil maintained above pH 5.5. Similarly, chromium is only slightly soluble in soil. Arsenic, selenium, tin and mercury are usually present in sludge in such small quantities that they do not pose a significant risk. Lead is toxic to animals but this element is not readily transferred from the root system of plants. Concern has been expressed that animals ingest significant quantities of soil and that sludge applied on the surface of pasture land could result in lead toxicity to grazing animals. However, there has been no evidence of deleterious health effects in sludge feeding trials with cattle (Kienholtz, 1980). The metals that pose a significant potential hazard are: cadmium, copper, molybdenum, nickel and zinc.

5.2.1 **Cadmium.** Of the five elements of greatest concern with respect to land application of sludge, it is widely accepted that cadmium presents the greatest risk to human health. It is a nonessential element which is highly toxic to plants and animals. During the past decade, concern over cadmium in the environment has increased because it has been linked to a variety of health disorders. Cadmium accumulates in the liver and kidneys of humans and animals and can cause renal tubular damage after chronic exposure. The possible hazard to humans from cadmium levels in plants causes greater concern than the toxicity to plants themselves; cadmium is generally not phytotoxic at the concentrations found in plants.

The main intake of cadmium by Canadians is through food, the range being 0.05 to 0.098 mg/d (Health and Welfare Canada, 1980). Since the World Health Organization recommended maximum permissible intake is 0.057 to 0.071 mg/d, a serious

TABLE 8 MAXIMUM PERMISSIBLE LEVELS OF HEAVY METALS IN SLUDGES ACCEPTABLE FOR USE ON AGRICULTURAL LANDS IN SEVERAL COUNTRIES (Webber et al., 1983)

Country*	Permissible Level (mg/kg dry weight)											
	Cd	Zn	Cu	Ni	Pb	Cr	Mn	Mo	Co	As	Se	Hg
Belgium	10	2 000	500	100	300	500	500	-	20	10	25	10
Canada**	20	1 850	-	180	500	-	-	20	150	75	14	5
Denmark	8	-	-	30	400	-	-	-	-	-	-	6
Finland	30	5 000	3 000	500	1 200	1 000	3 000	-	100	-	-	25
France	20	3 000	1 000	200	800	1 000	-	-	20	-	100	10
Germany	20	3 000	1 200	200	1 200	1 200	-	-	-	-	-	25
Netherlands	10	2 000	600	100	500	500	-	-	-	10	-	10
Norway	10	3 000	1 500	100	300	200	500	-	20	-	-	7
Sweden	15	10 000	3 000	500	300	1 000	-	-	50	-	-	8
Switzerland	30	1 000	1 000	200	1 000	1 000	-	20	100	-	-	10

*United Kingdom: Sludge for public distribution should not contain more than 20 mg Cd/kg dry wt. Sludge applied to pasture land should not contain more than 3 500 mgF/kg dry wt. and applied to pasture land, gardens and recreational areas should not contain more than 2 000 mg Pb/kg dry wt.

United States: Sludge applied to fruit and vegetable crop land should not contain more than: Cd, 25; Pb, 1 000; and polychlorinated biphenyls, 10 mg/kg dry wt.

**Values are for sludge and sludge-based commercial products containing $\leq$5% nitrogen (Standish, 1981).

TABLE 9 MAXIMUM PERMISSIBLE CUMULATIVE METAL LOADINGS TO AGRICULTURAL LANDS IN SEVERAL JURISDICTIONS (Webber et al., 1983, except where indicated)

Jurisdiction	Permissible Cumulative Loading (kg/ha)												
	Cd	Zn	Cu	Ni	Pb	Cr	Mn	Mo	Co	As	Se	Hg	B
Alberta[a]	0.8-1.5	150-300	100-200	12-25	50-100	50-100	-	-	-	-	-	0.2-0.5	5-10
British Columbia[b]	4	370	-	36	100	-	-	4	30	15	2.8	1.0	-
Ontario[c]	1.6	330	150	32	90	210	-	4	30	14	2.4	0.8	-
Canada[d]	4	370	-	36	100	-	-	4	30	15	2.8	1.0	-
Denmark	0.2	-	-	-	-	-	-	-	-	-	-	-	-
Finland	0.1	-	-	-	-	-	-	-	-	-	-	-	-
France	5.4	750	210	60	210	360	-	-	-	-	-	2.7	-
Germany	8.4	750	210	60	210	210	-	-	-	-	-	5.7	-
Netherlands	2.0	400	120	20	100	100	-	-	-	2	-	2.0	-
Norway	0.2	60	30	2	6	4	10	-	0.4	-	5	0.14	-
Sweden[e]	0.075	50	15	2.5	1.5	5	-	-	0.25	-	-	0.04	-
United Kingdom	5	560	280	70	1000	1000	-	4	-	10	5	2.0	4.5
United States	5-20	250-1000	125-500	50-200	500-2000	-	-	-	-	-	-	-	-

a Alberta Environment (1982)
b British Columbia (1982)
c OMAF/OMOE (1981)
d Standish (1981)
e Five-year loading; can be repeated.

effort must be made to ensure that the intake of cadmium through food and water is not increased by land application activities.

The amount of cadmium transferred from the soil to vegetation and seeds varies considerably from plant to plant. Similarly, environmental factors such as temperature, soil moisture and, most importantly, soil pH can modify the level and distribution of cadmium in the plant (Sheaffer et al., 1979; CAST, 1980). As with most metals, uptake of cadmium by plants is greater at lower pH (particularly below pH 6.5).

Because of the significance of cadmium levels in the human diet, guidelines and permits rely heavily on cadmium levels in sludge (Table 8) and total cadmium loadings to land (Table 9). The variation in permissible limits for cadmium indicates a degree of uncertainty about its possible adverse effects. However, it is generally agreed that cadmium loadings to land should be small to minimize adverse human and animal health effects.

5.2.2 **Zinc**. Zinc is essential for humans, animals and plants. It is a component of more than 70 known metalloenzymes. Chronic zinc poisoning in humans has not been reported (Health and Welfare Canada, 1980).

Zinc is relatively nontoxic to animals as well, with 500 ppm in the diet causing no toxic or other detrimental effects (CAST, 1976). Excessive zinc intake decreases the copper levels in the liver in ruminants.

As with cadmium, the uptake of zinc by plants is greater when the pH is below 6.5; availability to plants is inversely related to the organic content of the sludge. Zinc is not toxic to plants below concentrations of several hundred mg/kg.

Although zinc does not cause major toxicity problem in animals and humans, high levels in sludge applied to land will almost invariably result in significantly increased concentrations in crops (CAST, 1976).

5.2.3 **Copper**. Copper is essential in the human diet. The element is usually found in combination with proteins in the human body and has a role in erythrocyte formation, release of tissue iron, and in the development of several body tissues. Chronic copper toxicity has not been recorded, even when the diet contained relatively high copper levels (Health and Welfare Canada, 1980); thus, slight increases in copper levels in food are no cause for concern to humans.

Among domestic animals, copper toxicity can occur in sheep, cattle, swine and poultry, with sheep being the most susceptible species. Since copper accumulation in the liver is exacerbated by insufficient levels of molybdenum in food, it can be minimized by maintaining adequate levels of molybdenum (CAST, 1976). High levels of copper, in a diet supplemented with zinc and iron, may induce weight gain in chickens and pigs, with some accumulation of copper in the liver (CAST, 1976).

Although copper is essential to plants, application of sludge containing high copper concentrations can cause plant toxicity and lower crop yields. Usually plant toxicity will occur at levels lower than would cause animal toxicity. Fortunately, in most cases, little transfer of copper from the roots to the above-ground portion of the plant occurs.

5.2.4 **Nickel.** Although nickel is essential for animals and thus is probably also essential for humans (National Academy of Sciences, 1980), no nickel deficiency has ever been recognized in humans. This element is relatively nontoxic; gastrointestinal irritation is the first symptom of high oral doses.

In contrast with low toxicity to animals and humans, nickel is taken up from the soil by plants and becomes phytotoxic at about 50 mg/kg in plant tissues. This plant uptake may be enhanced by the presence of organic matter in sludge (Cunningham et al., 1975). As with most metals, nickel uptake is greatly enhanced below pH 6.5; if the pH is maintained above 6.5 at the sludge-application site, nickel should not cause toxicity to plants or pose a threat to the food supply.

5.2.5 **Molybdenum.** Molybdenum is essential to humans in trace quantities; it is an integral part of several essential metalloenzymes such as xanthine oxidase. The requirement is almost always met in the normal diet. Molybdenum is not considered very toxic to humans; however, extremely high levels in the diet can result in chronic toxicity, mainly manifested as arthralgia (National Academy of Science, 1980).

Cattle are the farm animals most susceptible to molybdenum toxicity; sheep are less susceptible than cattle, and horses and pigs are least susceptible. Forages with molybdenum concentrations greater than 10-20 mg/kg may cause molybdenosis in ruminants. Excessive molybdenum in the diet causes copper and phosphorus deficiencies, conditions that can be remedied by appropriate copper and phosphorus supplements.

Sewage sludges generally contain low levels of molybdenum and are not likely to cause molybdenosis in animals except when high molybdenum sludges (>40 mg/kg) are applied on land used to grow forage which comprises the major part of the animal diet (CAST, 1976). Plant toxicity does not occur even where such high Mo levels are applied.

5.2.6 **Summary.** Of all metals present in treated wastewater and sludge, cadmium is considered to present the most significant potential risk because of its mammalian toxicity, uptake in plants, presence in significant quantities in sludge and continuous plant availability for years after application on land. To prevent toxicity to humans or animals from crops grown on treated agricultural lands, guidelines relating to metal concentrations in sludge and maximum additions to land have been developed (OMOE/OMAF, 1981; Alberta Environment, 1982). These guidelines and those of other jurisdictions are shown in Tables 8 and 9. Such guidelines should be followed scrupulously and accurate records kept of treated wastewater and sludge applications to ensure maximum health protection and minimum adverse environmental impact.

5.3 Organic Chemical Contaminants

The aspects of sludge and treated wastewater application to land that are least understood, but which are now being examined in more detail, are the concentration, fate and effects of synthetic organic compounds. The compounds being studied include polynuclear aromatic hydrocarbons, chlorinated phenolics, pesticides, polybrominated biphenyls (PBBs), polychlorinated biphenyls (PCBs), phthalates and other potentially toxic persistent materials (OMOE/OMAF, 1981). Unlike natural organic materials which abound in raw sewage, many of the synthetic organics resist biodegradation and persist in the sludge and treated wastewater.

Environment Canada has developed a "Working List of Suspect/Priority Toxic Chemicals" comprising 150 compounds or groups of compounds. It was derived from existing Health and Welfare Canada, Environment Canada, Great Lakes Water Quality Board and United States of America Environmental Protection Agency (U.S. EPA) priority pollutant lists. The U.S. EPA priority pollutant list identifies 114 organics. They enter the sewage system from domestic and industrial sources and may accumulate in sludge. They are potentially hazardous to humans and animals for one or more of the following reasons:

1) They have low water solubility and do not move readily in soil.
2) They are relatively stable in soil because they are resistant to microbial degradation.
3) They are fat soluble and bioaccumulate in tissue.
4) They pass up the food chain (soil to plants to animals to man).
5) They are highly toxic to mammals; many are carcinogenic, mutagenic and teratogenic.

With the exception of polychlorinated biphenyls (PCBs), very little is known about the concentrations and fate of toxic organics in treated wastewater and sludge applied to land in Canada. Recently, however, Environment Canada and the Ontario Ministry of the Environment have initiated studies to develop analytical methods for the complete range of toxic organic compounds and to measure their concentrations in environmental samples.

PCBs in wastewater are concentrated in the sludge during treatment (Shannon et al., 1976). Land application of some Ontario sludges has caused small but significant increases in the PCB contents of receiving soils; however, there was no evidence of uptake by crops (Webber et al., 1983). PCBs are absorbed through the gut in humans and animals; they have been shown to be mutagenic, teratogenic and carcinogenic in animal studies (Health and Welfare Canada, 1980). Concentrations of other selected toxic organics in Canadian treated wastewaters and sludges are reported in Sections 7 and 8, respectively, of this manual, but crop uptake data are not available.

Once applied to land, organic substances are subject to photo-oxidation, volatilization and biodegradation that may significantly alter their structure and toxicity characteristics. Due to the myriad of compounds present, no generalizations can be made about their ability to be translocated into plants. It is known, however, that some toxic organic compounds are taken up into plants through the roots and translocated to aerial portions (Majeti and Clark, 1981). Usually the levels attained in the plant are only a fraction of that present in the soil.

5.3.1 **Organic Chemicals in Treated Wastewater.** Surveys of Canadian sewage treatment plant effluents by Environment Canada have indicated the presence of a number of toxic organic chemicals at low concentrations (Section 7). Most compounds detected were at concentrations between 1 and 10 µg/L. Compounds detected most often included volatile organics such as chloroform and benzene, polynuclear aromatic hydrocarbons, chlorophenols and phthalates. The significance of these low levels of toxic organics for wastewater irrigation is not known.

5.3.2 **Organic Chemicals in Sludge.** A survey of Canadian wastewater treatment plant sludges for toxic organic chemicals by Environment Canada indicates the accumulation of numerous compounds at concentrations three to four orders of magnitude higher than present in the effluents. Compounds most likely to accumulate appear to be phthalates, polynuclear aromatic hydrocarbons and chlorinated compounds (see Section 8). The significance of these compounds in sludge utilization is not known.

5.3.3 Summary. There are significant gaps in our knowledge with respect to the fate of organic contaminants in wastewater and sludges applied to land. Although there is no evidence at present of adverse human health effects, continued vigilance is warranted. Research programs have been undertaken in Canada and the United States to develop analytical methods for toxic organic compounds in environmental samples and to determine their fate and effects. There should be periodic analyses of material to be applied on agricultural land to ensure that excessive accidental or intentional contamination of the wastewater has not occurred, and historical records of application should be maintained.

5.4 Pathogenic Organisms

The potential risk of infection to humans, animals and plants from land application of treated wastewater and sludge is attributable to the presence of pathogenic organisms in the raw wastewater (sewage). The number of pathogens in sewage varies according to the concentration of sewage and the number of persons shedding these organisms at a given time. In Canada, it has been shown, for example, that the number of enteroviruses present in wastewater increases in the summer and autumn when these infections are widely prevalent in the population (Subrahmanyan, 1977).

Little evidence exists to show that disease is transmitted by land spreading of treated wastewater and sludge. Documented disease transmission to humans from land application programs is mainly related to the use of raw wastewater on land. Some animal disease transmission has been found related to land application of untreated and partially treated wastewater.

Pathogens that pose potential hazards to human and animal health enter municipal sewage from a variety of sources. Humans infected with enteric diseases are a major source. Others are effluents from abattoirs, rendering plants and dairies, and animal feces that have been flushed down toilets or deposited on yards or streets and carried into the sewage system via surface water drainage. Sewage treatment practices reduce the number of pathogenic organisms but evidence is abundant that detectable amounts of most types can occur in treated wastewaters and sludges. Pathogenic organisms are classified as bacteria, viruses, helminths and protozoa (Table 10).

This subsection identifies and discusses the pathogenic organisms relevant to land application of treated wastewater and sludge; evaluates, insofar as possible, their implications for the health of workers, the public at large, and animals and plants; and suggests management strategies to minimize risk.

TABLE 10 ORGANISMS OF HEALTH CONCERN THAT MAY BE PRESENT IN SEWAGE AND SLUDGE FROM CANADIAN COMMUNITIES*

Organisms	Disease	Reservoirs
BACTERIA		
Salmonella (ca. 1 700 types)	Typhoid fever, paratyphoid fever, enteritis, salmonellosis, food poisoning	Man, domestic and wild animals, birds
Shigella	Shigellosis (dysentery)	Man
Escherichia coli (enteropathogenic types)	Gastroenteritis	Man, domestic animals
Clostridium	Gas gangrene, tetanus, botulism, food poisoning	Animals, fish
Leptospira	Leptospirosis	Man, domestic and wild animals
Mycobacterium	Tuberculosis, skin granuloma	Man, domestic and wild animals
Pseudomonas	Local infection	Man
Yersinia enterocolitica	Epidemic gastroenteritis	Man, domestic and wild animals, lower animals
VIRUSES		
Enteroviruses		
Poliovirus (3 types)	Paralysis, meningitis, fever	Man
Coxsackievirus A	Herpangia, respiratory disease, meningitis, fever	Man
Coxsackievirus B (6 types)	Myocarditis, congenital heart anomalies, rash, fever, meningitis	Man
New enteroviruses (4 types)	Meningitis, encephalitis, respiratory disease, acute hermorrhagic conjunctivitis, fever	Man

TABLE 10 ORGANISMS OF HEALTH CONCERN THAT MAY BE PRESENT IN SEWAGE AND SLUDGE FROM CANADIAN COMMUNITIES (Cont'd)

Organisms	Disease	Reservoirs
Hepatitis A	Infectious hepatitis	Man, other primates
Gastroenteritis virus type agents, (2 types)	Norwalk epidemic, vomiting and diarrhea, fever	Man
Rotavirus (Reoviridae family)	Epidemic vomiting and diarrhea, mainly of children	Man, domestic animals
Reovirus (3 types)	Not clearly established	
Adenovirus (more than 30 types)	Respiratory disease, eye infections	Man
Parvovirus (adeno-associated virus, 3 types)	Associated with respiratory disease in children; etiology not clearly established	Man
PROTOZOA		
Balantidium coli	Balantidiasis	Man, swine
Entamoeba histolytica	Amoebiasis	Man
Giardia lamblia	Giardiasis	Man, domestic and wild animals
HELMINTHS		
Nematodes (Roundworms)		
Ascaris lumbricoides	Ascariasis	Man, swine?
Ancylostoma duodenale	Ancylostomiasis	Man
Necator americanus	Necatoriasis	Man
Ancylostoma briziliense (cat hookworm)	Cutaneous larva migrans	Cat

TABLE 10 ORGANISMS OF HEALTH CONCERN THAT MAY BE PRESENT IN SEWAGE AND SLUDGE FROM CANADIAN COMMUNITIES (Cont'd)

Organisms	Disease	Reservoirs
Ancylostoma caninum	Cutaneous larva migrans	Dog
Enterobius vermicularis (pinworm)	Enterobiasis	Man
Strongyloides stercoralis	Stronglyloidiasis	Man, dog
Toxocara cati (cat roundworm)	Visceral larva migrans	Carnivores
Toxocara canis	Visceral larva migrans	Carnivores
Trichurus trichiura (whipworm)	Trichuriasis	Man
Cestodes (Tapeworms)		
Taenia saginata (Beef tapeworm)	Taeniasis	Man
Taenia solium (Pork tapeworm)	Taeniasis	Man
Hymenolepis nana (dwarf tapeworm)	Taeniasis	Man, rat
Echinococcus granulosis (dog tapeworm)	Unilocular echinococciosis	Dog
Echinococcus multilocularis	Alveolar hydatid disease	Dog, carnivores

* After Carrington (1978), Anon. (1979), WHO Scientific Group (1979), Robinson (1980), OMOE (1980).

5.4.1 **Bacteria.** Salmonella probably constitute the most important group of bacterial pathogens to be considered in relation to land application of treated wastewater and sludge. There are more than 1 700 types of Salmonella spp. which can be pathogenic for man and animals. This is the most widely-spread pathogenic bacterium in the environment and is a major cause of disease in Canada. The weekly disease report of Health and Welfare Canada reports more than 7 000 diagnosed cases of salmonellosis per year, a figure which may represent only 1% of total cases (Vanderpost and Bell, 1977). Infection requires a large dose of organisms for healthy adults (Table 11); the resulting disease can range from gastroenteritis to septicemia, enteric fever and, rarely, to meningitis and death. Transmission to man may occur through water, food (including meats and poultry, dairy products, vegetables, fruits and grains), animals and other humans.

TABLE 11 DOSES CAUSING A 50% INFECTION RATE FOR SELECTED HUMAN PATHOGENS (Sorber, 1982)

Organism	50% Infective Dose	Mode of Administration
Salmonella spp.	$10^5 - 10^8$	Oral
Shigella	$10^1 - 10^2$	Oral
Entamoeba coli	10 - 100	Oral
Giardia lamblia	1 - 10	Oral
Poliovirus 3 (Fox)	4 ($TCID_{50}$)	Stomach gavage
Poliovirus 1 (Sabin)	72 ($TCID_{50}$)	Oral
Echovirus 12	35 (PFU)	Oral
Coxsackievirus A21	28 ($TCID_{50}$)**	Nasal
Adenovirus 4	1 ($TCID_{50}$)	Nasal

* Studies conducted on healthy adults except for polioviruses which were on healthy infants.
TCID = Tissue culture infective dose.
PFU = Plaque-forming units.
** Infective dose was found to approximate the illness dose.

Because Salmonella organisms can be carried by apparently healthy humans and animals after recovery from acute infection, they frequently can be isolated in domestic sewage from large urban areas. Furthermore, human salmonellosis is highly dependent upon the large reservoir of animal infection and is usually the result of eating meat that has been contaminated from intestinal contents rather than primary contamination of the tissue.

About 80-90% of the Salmonella organisms in wastewater are removed to the sludge during primary treatment. Adequate secondary treatment and disinfection of effluent and anaerobic digestion of sludge can ensure that Salmonella levels are sufficiently low for land application.

Shigellosis is an acute diarrheal disease that affects about 2 000 Canadians each year. It is often associated with institutions and poor socio-economic status. Shigella are not normally associated with animals other than man. As with Salmonella, transmission to man may be by food, water, or contact with other humans although the infective dose is lower than for Salmonella (Table 11). However, because Shigella tend to survive poorly in the environment and are not a major pathogen of domestic animals, they are considered to present a less serious health hazard relative to land application than Salmonella.

While Escherichia coli is normally present in the gut of humans and many animals, some types, namely the enteropathogenic serotypes, can cause serious diarrhea in children and can also cause gastroenteritis and urinary infections in adults. This organism has been the cause of many outbreaks due to drinking water contamination (Geldreich, 1972). E. coli is not usually capable of extensive regrowth in the environment and is sensitive to most disinfection processes. It is not expected to be a major problem relative to land application of treated wastewater and sludge.

The Leptospira group of coil-shaped motile bacteria cause leptospirosis in humans after entering the body through cuts or abrasions. This disease may be manifested by acute infections of the kidneys, liver and central nervous system. The organism attacks domestic and wild animals in addition to man. Although the disease can occur at any time, most outbreaks in North America have been associated with swimming in polluted water (Geldreich, 1972). The most likely source of high levels of contamination in recreational waters is urine from infected animals. This pathogen is considered to be a greater potential problem in animal waste than in domestic sewage. The organism is a strict anaerobe and is sensitive to environmental stress; it is not expected that it would survive well on land.

Mycobacteria are responsible for tuberculosis, skin ulcers and leprosy in humans and tuberculosis in animals with possible complications, including abortion, decreased milk production, and poor weight gain. Infection can be caused by ingestion or inhalation of bacilli released into the sputum, milk, or discharges from infected animals or humans. Infection from contaminated water or waste is thought to be uncommon, perhaps because the long incubation period in the case of tuberculosis tends to obscure the source of the contamination. The main concern associated with mycobacteria in wastewater treatment and land application is their extreme resistance to disinfection and to inactivation in the environment. They can persist for many months in treated wastewater, and their survival is enhanced by low water temperature and high organic concentrations. There is little evidence to suggest increased infection rates resulting from land application.

5.4.2 **Viruses.** A wide range of viruses is known to be present in raw sewage, the result of excretion and secretions from infected members of the population. Virus particles cannot replicate outside the host cells, so there is no possibility of replication in wastewater. Most viruses are host-specific, i.e., not transmissible between species. The possible exceptions to this are reoviruses, of which identical serotypes have been isolated from a variety of animals including cattle and swine; and rotaviruses, which exhibit similarity between animal and human strains.

Viruses are usually solids-associated and concentrate in primary sludge as well as sludge from activated sludge systems. They are moderately resistant to chlorination; under conditions where 99.9% to 99.9998% reduction of fecal coliforms have been obtained, virus reductions of only 90% to 99% have been obtained (Berg and Metcalf, 1978). Another study showed E. coli to be 400 times more sensitive than poliovirus to hypochlorous acid (Scarpino et al., 1972). Viruses studied thus far are also somewhat resistant to mesophilic sludge digestion but can be virtually eliminated by heat treatment and composting. Solar irradiation, predation and adsorption to particulates further reduce the risk from viruses after land application (Table 12), although they have been reported to migrate as far as 1.4 m through fine textured soil (Moore et al., 1981).

There is little evidence to indicate that viruses present a health hazard as a result of land application. Although, in theory, one virus particle can infect the human or animal host (Table 11), in fact, significantly higher doses are usually required to cause detectable illness. In many cases the immune system of healthy individuals restricts the virus replication so that only subclinical infection takes place.

5.4.3 **Helminths.** Helminths, parasitic intestinal worms, are of concern primarily in wastewater sludge because of the size, density and environmental resistance of the eggs (ova). The organisms of importance in sludge application fall into two distinct groups, the nematodes (roundworms) and cestodes (tapeworms). Although helminth diseases are not

TABLE 12 SURVIVAL TIMES OF PATHOGENIC MICROORGANISMS ON PLANTS AND SOIL*

Organism	Media	Survival Time (days)
Coliforms	Soil surface	38
	Vegetables	35
	Grass and clover	6-34
Streptococci	Soil	35-63
Fecal streptococci	Soil	26-77
Salmonella typhi	Soil	1-120
	Vegetables	<1-68
Salmonella, other than typhi	Soil	15->280
	Vegetables and fruits	3-49
Shigella	Vegetables	2-10
	Grass (raw sewage)	42
Mycobacterium tuberculosis	Soil	>180
	Pasture (manured)	60-180
Ascaris ova	Soil	Up to 7 years
	Vegetables and fruits	27-35
Entamoeba histolytica cysts	Soil	6-8
	Vegetables	<1-3
Ancylostoma larvae	Soil	15-42
Enteroviruses	Soil	8-12
	Vegetables	4-6

* After Burge and Marsh (1978), Anon. (1978), Anon. (1979).

notifiable illnesses, the British Columbia Provincial Laboratories (Bowmer, 1979) reported the following numbers of laboratory isolations of intestinal helminths in humans from 1976-1978: Trichuris trichiura, 2545; Ascaris Lumbricoides, 725; Strongyloides, 189; Taenia species, 28; Hymenolepis nana, 287. Similar data for other provinces have been reported (Laird et al., 1980).

Nematodes comprise a large group of organisms which do not require an intermediate animal host and which are transmissible to man or animals. The more significant of these are listed in Table 10. Sludge is considered a vector for both Ascaris and Toxocara species (WHO, 1981). Of these, Ascaris lumbricoides, which can infect the small intestine of man, is the major concern, because the eggs are among the most resistant biological entities present in sewage sludge. Survival of these eggs in soil for up to seven years has been documented (Table 12) although much shorter survival periods may be common. A study of nematode eggs on land in Alberta where sludge had been surface applied showed that the majority of the parasite eggs could be found in the top 2.5 cm of soil (Lehman et al., 1981). The distribution of parasite eggs was non-random, with "pockets" of high densities. The average egg concentration per kg of soil decreased by more than 70% per year in one phase of the study, although the accuracy of the data obtained was questioned due to the low recovery efficiency inherent in the method (4-8% recovery). Most of the parasitic stages found were eggs from domestic animals, with strongyles (gastrointestinal nematodes) predominant and ascarids (Toxocara, Ascaris and Toxascaris species) present in lesser numbers.

There are no accurate estimates of the concentrations and types of nematodes in Canadian sludges. Lehman et al. (1981) reported the following levels of helminths in digested sludges: strongyles 500-2000/L, Ascaris spp. 0-500/L, Taenia spp. 0-500/L. They also reported the following concentrations of helminths in lagoon sludge: strongyles 14 000-110 000/kg dry wt., Ascaris spp. 0-2 000/kg, Toxocara spp. 0-2000/kg. Graham (cited in Vajdic, 1978) has regularly isolated viable Trichuris and Ascaris spp. eggs in southern Ontario digested sludges, at 20-40/L and 20-280/L, respectively. Arthur et al. (1981) reported the following levels of nematodes on a dry weight basis in lagooned, 14-day anaerobically digested (35°C), Illinois sludge: Ascaris spp. 2030/kg, Toxocara spp. 1728/kg, Toxascaris leonina 478/kg, and Trichurus spp. 360/kg. All four genera were capable of embryonation (20-64%) after anaerobic digestion.

Infection by nematodes requires direct contact with or ingestion of sludge or soil containing eggs. This factor, plus the gradual decline in numbers of eggs after exposure to the environment, should ensure that proper application of treated sludge to land for field crop production is not likely to present an undue risk of human infection.

The beef tapeworm, Taenia saginata, and the pork tapeworm, T. solium, may be the most serious biological health risks associated with sludge application. In both cases man is the definitive host, with the animals being the intermediate host. The adult tapeworms reside in the infected human gut and up to a million eggs are shed in gravid segments per day. Ingestion of these ova by the intermediate (animal) host results in hatching of the eggs in the intestine and migration of the larvae to the skeletal muscles where they form cysticerci called measles. The ingestion of inadequately cooked "measley" meat allows the completion of the life cycle in man.

Conventional sewage treatment does not eliminate the animal health hazard from tapeworm ova in treated effluent and sludge although anaerobic digestion may deactivate up to 97% of these ova in sludge (Burge and Marsh, 1978). Incidents have been reported where pastures irrigated with raw sewage caused infections in cattle (Greenberg and Dean, 1958). The survival time of tapeworm ova on land is not well documented, and is certainly dependent upon humidity, sunlight and other environmental factors. Some data indicate the loss of infectivity for calves by 17-18 weeks after application of sludge on grasssland (WHO, 1981).

5.4.4 Protozoa. A few species of enteropathogenic protozoa exist which are excreted by infected individuals (Table 10) and appear in raw sewage. Their cysts, like helminth ova, are resistant to stresses from disinfectants and the environment and have been found in significant quantities in sludge in the United States (Little, 1980). There appears to be little direct human health hazard from protozoan cysts applied on land for field crops, but a low risk to animals of direct ingestion exists if the land is used for pasture too soon after sludge application.

5.4.5 Biological Quality of Treated Wastewater. The microbiological quality of an effluent is a function of the type and efficiency of the sewage treatment process used as well as the initial levels of pathogens in the raw wastewater. Since the pathogens are not usually measured directly, levels of indicator organisms are used as a guide to the effluent quality. While levels of fecal coliforms of less than about 200-1 000 per 100 mL are considered ideal for irrigation, levels of up to 54 000/100 mL have been used at Taber, Alberta (Bole, 1975) with no apparent ill effects. Fecal coliforms are considered more reliable as an indicator of effluent quality than total coliforms because of their greater specificity for fecal pollution, but they cannot be considered a reliable indicator of the presence of viruses, cysts, or ova because of the greater sensitivity of fecal coliforms to chlorination and other environmental stresses than the latter pathogens. Thus, high levels of fecal coliforms (and other bacterial indicators such as fecal streptococci) can be taken as presumptive evidence of the presence of pathogens; however, absence cannot be used to infer the absence of pathogens.

It has been demonstrated that pumping can diminish levels of bacteria in treated effluent (Biederbeck, 1979), but little is known about the effects on viruses, cysts and ova. Where spray irrigation is employed, the formation of aerosols and transport by wind is a primary health concern. Pathogenic enteric viruses have been detected 100 m from irrigation sites (Teltsch et al., 1980), while enteric bacteria have been found 350 m downwind (Katzenelson and Teltsch, 1976). Aerosol generation and transport can be minimized by judicious selection of spray equipment so as to minimize wind dispersal. Normally, spraying is not permitted during high winds. Solar radiation and dessication of aerosol droplets are effective in deactivating most pathogens under ideal conditions, but the use of land buffer zones to separate irrigation areas from inhabited areas is considered prudent.

Once on the soil, most enteric organisms are eventually deactivated by natural environmental stresses. Relatively few of these microorganisms (only bacteria and fungi) are suited to proliferation in soil. The majority are affected by ultraviolet light, predation, dessication and adverse temperatures in such a way that they are no longer recoverable by normal microbiological techniques (Bell and Bole, 1976). Some typical survival times of pathogenic microorganisms are given in Table 12. Of the bacteria, Salmonella and Mycobacterium survival times in the order of 200 days are not uncommon. Survival of some helminth ova are extraordinary, with up to seven years being reported.

The major routes of potential exposure to pathogens in irrigation water are contact, inhalation of aerosols, consumption of water from a contaminated aquifer and consumption of portions of plants or animals which have been contaminated by irrigation water. An excellent review of the historical outbreaks from such contamination has been published (Parsons et al., 1975) and indicates that most were associated with gross contamination with fecal material or raw sewage. Several major studies have been carried out to determine whether irrigation causes excess illness in the exposed population. In 1976, Katzenelson and co-workers reported an increase in enteric diseases in Kibbutzim in Israel that used non-disinfected partially treated wastewater for irrigation. A subsequent study of the same region, however, failed to reveal the same trends (Shuval and Fattal, 1980). Other epidemiological studies of wastewater aerosols have been made, often in the region adjacent to a wastewater treatment facility (Camann et al., 1980; Johnson et al, 1980; Sekla et al., 1980). On the basis of these and other studies it is concluded that there is little risk of illness from aerosols from properly treated effluent. However, carefully controlled prospective epidemiological studies have been carried out only recently , and they are somewhat limited in their sensitivity (Cabelli et al., 1976).

On the basis of microbiological considerations, it is essential that effluent irrigation not be used on any products that could be consumed without cooking, and care should be exercised in the application of such material on crops for direct human consumption even when they are normally cooked before consumption.

A summary of Canadian, U.S. and WHO guidelines for irrigation water quality is presented in Table 13. Most jurisdictions specify either treatment techniques to be used or bacterial indicator density limits (total and/or fecal coliforms) that must not be exceeded. While low indicator bacteria levels are not necessarily indicative of the absence of pathogens, they are useful in monitoring the adequacy of treatment. Experience has shown that a combination of adequate effluent treatment and good management practices can prevent a significant health risk. In special cases (such as areas where public contact is expected, or for use on fruit crops) it may be possible to use treated wastewater that has undergone a high degree of treatment followed by disinfection. This approach, in use in California, may be applicable in other arid areas where sources of fresh water are difficult or costly to locate and develop.

5.4.6 **Biological Quality of Sludge.** The quality of sludge is highly dependent on the type of sewage and treatment process it is derived from and the subsequent processing it has undergone. A recent study (Dudley et al., 1980) examined the spectrum of bacteria present in a high rate and a standard rate anaerobically digested sludge and another which was lagooned after being digested anaerobically. Their data show that a large number of potentially harmful organisms persisted in the treated sludge. Studies by Subrahmanyan (1977) on 101 digested Ontario sludges revealed that 16 percent still contained pathogenic human viruses. Considerable evidence indicates the persistence and long-term survival of helminth eggs and protozoan cysts in both raw and treated sludges (Little, 1980; Sholten and Young, 1975; Parsons et al., 1975; Laird et al., 1980; Arthur et al., 1981).

Several methods of stabilization and pathogen reduction can be employed in preparing sludge for land application. Anaerobic digestion, with or without long-term lagooning, is reasonably effective for pathogen inactivation. However, mechanical methods of heating sludges to about 70°C, although not used in Canada, are superior (Table 14). Bacteria and viruses are effectively reduced by most methods of disinfection, whereas Ascaris ova are only appreciably diminished by temperatures greater than 50°C for 1 h or more (Robinson, 1980).

TABLE 13 GUIDELINES FOR IRRIGATION WATER QUALITY FOR AGRICULTURAL USE (Parson et al., 1975; OMOE, 1978)

Jurisdiction	Acceptable Water Quality
Canada (Ontario)	Irrigation water should be of such quality as to meet the objectives for swimming and bathing uses (water should not cause diseases; fecal coliforms less than 100 per 100 mL; total coliforms less than 1 000 per mL).
Canada (Alberta)	For vegetable crops, geometric mean should not exceed 1 000 total coliforms per 100 mL nor 200 fecal coliforms per 100 mL, nor exceed these numbers in more than 20 percent of the samples, nor exceed 2 400 total coliforms per 100 mL on any given day.
USA (California)	For field crops, the water should have at least the quality of primary effluent. For irrigation of parks and other land with public access, the water shall be an adequately disinfected wastewater (median MPN of <23 total coliforms per 100 mL).
USA (Georgia)	Fecal coliform levels not to exceed 10 000 per 100 mL over a 30-day period and not to exceed 40 000 per 100 mL in more than 5% of samples.
USA (Massachusetts)	Coliform bacteria not to exceed an average of 1 000 per 100 mL in a month, nor 2 400 per 100 mL in more than 20% of samples.
USA (Minnesota)	Crops, vegetation and truck garden crop irrigation water not to exceed 5 000 MPN total coliforms per 100 mL.
USA (Nebraska)	For agricultural irrigation, not to exceed a geometric mean value of 10 000 total coliforms or 2 000 fecal coliforms per 100 mL. Not more than 20% of samples to exceed 20 000 total or 4 000 fecal coliform bacteria per 100 mL.
USA (North Carolina)	For fruits and vegetables, fecal coliforms shall not exceed a log mean of 1000 per 100 mL during a 30-day period, nor exceed 2000 per 100 mL in more than 20% of the samples.
World Health Organization	It was assumed that only a limited health risk would result from the unrestricted irrigation of agricultural crops with sewage effluents having a bacteriological quality of 100 coliform organisms per 100 mL. Primary treatment of sewage was considered satisfactory for the irrigation of crops not for direct human consumption; for irrigation of produce, primary and secondary treatment should be used, preferably followed by filtration or polishing and disinfection.

TABLE 14 DEACTIVATION OF PATHOGENS BY PROCESSES EMPLOYED TO STABILIZE SLUDGES (Farrell and Stern, 1975)

Process	Effectiveness		
	Pathogen Deactivation	Putrefaction Potential	Odour
Anaerobic digestion	Fair	Good	Good
Aerobic digestion	Fair	Good	Good
Lime treatment	Good	Fair	Good
Pasteurization (70°C)	Excellent	Poor	Poor
Ionizing radiation	Excellent	Poor	Poor
Heat Treatment (195°C)	Excellent	Poor	Poor
Composting (60°C)	Good	Good	Good
Long-term lagooning of digested sludge	Good	-	-

The survival of organisms in sludge applied on land is similar to that of organisms applied in treated wastewater (Table 12) except that the solids in the sludge can have a protective effect (as with the inclusion of viruses within clumps). Lime treatment of sludge results in high pH and a high proportion of bacterial and virus kill.

Exposure to pathogenic organisms in sludge can occur through direct contact or by ingestion of vegetables, fruit or water that have been contaminated. In addition, the consumption of meat or dairy products from animals exposed to these organisms poses a potential threat to humans. In some ways, the exposure routes to pathogens in sludge are more limited than those from effluent irrigation. Spray drift, for example, is not a problem, nor is it customary to apply sludge to crops during the growing season when the material could adhere to the growing plants.

The degree of health risk is determined to a large extent by the types and numbers of pathogens in the sludge, the amount applied, climatic conditions, soil conditions and the subsequent use of the land. In a three-year study of viral infections in farmers exposed to sewage sludge, Hamparian et al., (1982) concluded that the health risk from viruses is minimal. There are few reports of human infection attributable to sludge application, although at least one case of human infection with tapeworms from cattle pastured on land treated with digested sludge has been reported (cited in Braude et al., 1978). The possibility for contact with pathogenic organisms may be minimized by subsurface injection of treated sludge rather than surface application, although further work should be done on pathogen survival.

A summary of international guidelines on the suitability of sludge for land application is presented in Table 15. Although some differences can be noted, digestion, stabilization or disinfection are usually required for all types of land application. Extended periods of time are required before grazing is permitted, largely due to helminth ova survival. If these and similar guidelines are followed, with good sludge and land management practices, it is considered that the risk of animal and human infection is minimal.

5.4.7 **Summary.** The organisms of greatest health concern associated with land application of wastewater and sludge are Salmonella, due to their prevalence and pathogenicity; Ascaris, due to the extreme resistance of the ova; Taenia, due to cattle exposure; and viruses, due to their ability to resist deactivation and to penetrate the soil, and the difficulty in monitoring them. Notwithstanding the concerns noted here, there is little evidence to incriminate treated wastewater irrigation or sludge application in disease outbreaks when treatment and application are performed in a careful and controlled manner. However, further studies and constant vigilance are required to ensure that human health is adequately protected.

TABLE 15 GUIDELINES FOR APPLICATION OF SLUDGES TO AGRICULTURAL LAND (Commission of European Communities, 1981; Alberta Environment, 1982)

Jurisdiction	Type of Sludge Acceptable/Guidelines
Canada (Ontario)	Only digested or stabilized sludges acceptable. Land not to be used for fruit, vegetable or grazing within 6 months of application by sheep and swine and 2 months by horses and dairy and beef cattle.
Canada (Alberta)	Only digested or stabilized sludges, or sludges stored >6 months or having a volatile solids content <60% of the total solids are acceptable. Direct grazing not recommended for 3 years following application. Not to be used on land for tobacco, root crops, food eaten raw.
United States (EPA)	Sludges must undergo processes to remove pathogens (chemical, physical, biological or thermal treatment). Sludges containing hospital wastes should be pasteurized, irradiated, composted, stored long-term, or pH raised to 12. Further treatment required if human food to be grown in 18 months.
United States (Wisconsin)	Raw sludge not to be used. Root crops or crops to be consumed raw not to be grown within 4 years of application. Milk cows should not be grazed until 2 months after application; other animals 2 weeks.
United Kingdom	Raw sludge may only be used for production of animal feed and food crops to be cooked. On pasture, delay required between application and grazing: 6 months for untreated and 3 weeks for treated sludges. Salad crops not to be sown within 12 months of sludge application.
Netherlands	Only treated sludges to be used on pasture land and no-grazing period of 6 weeks.
Switzerland	On grassland during the growing season only pasteurized sludge; otherwise stabilized sludge.
Denmark	Raw sewage not acceptable. Stabilized sludges only allowed for parks, arable and industrial crops, and pasture. Sludges containing abattoir wastes to be disinfected for use on pasture and crops for consumption raw.
Finland	Raw sludge not acceptable. Biological or lime stabilized or composted sludge acceptable for parks, arable land and industrial crops, but not recommended for pasture or crops for consumption raw.
Norway	Raw sludge not recommended. Biological or lime stabilized sludge acceptable for parks, arable land and industrial crops, but to be left 2 years before grazing pasture or growing crops for consumption raw. Composted or heat-treated sludges generally acceptable.
Sweden	Raw sludge acceptable for immediate incorporation into arable land far from populated areas. Stabilized sludge acceptable for arable land. Disinfected sludges acceptable for all agricultural and horticultural uses.

6 CROP CONSIDERATIONS

6.1 Introduction

Land application of treated wastewater and sludge presents the opportunity to recycle resources while producing an economic return from marketable crops. Application of wastewater can be geared to meet the nutrient and water requirements of crops. Sludges can provide nutrients for plant growth and organic matter for soil conditioning. Depending on effluent application methods, crop cover provides a means of controlling erosion.

However, land application systems for wastewater and sludge can create potential production problems due to flooding, lodging, salinity, microbial contamination, and excess nutrients. Many of these problems can be avoided by proper management practices.

This section discusses the benefits and risks of crop production in association with land application of treated municipal wastewater and sludge.

6.2 Crop Production Requirements

In any crop production system, nutrient and water requirements are two essential factors that must be considered.

6.2.1 **Nutrients.** The major nutrients required by crops are nitrogen, phosphorus, and potassium. These nutrients can be replenished in the soil by growing legume crops that fix nitrogen in the soil from the air, or by adding chemical fertilizer, farm wastes such as animal manure, and urban wastes such as municipal effluent and sludge. Micronutrients are generally not required because these elements are abundant in most soils; however, deficiencies may arise during effluent use.

Crop removal of nitrogen and phosphorus varies depending upon crop type and yield, and the amount of plant material harvested. Nutrients removed from soil by harvesting must be replaced if soil productivity is to be maintained. Nutrient removals by selected crops are given in Table 16.

6.2.2 **Water.** Water is essential for plant growth. The amount of water required varies with crop type and location. For optimum plant growth, the water requirement that is not met by natural precipitation must be supplied by irrigation. The irrigation requirement is generally defined as the difference between the potential for water loss by evapotranspiration and the amount of water supplied by precipitation. Typical water requirements for various crops grown on the Canadian prairies are given in Table 17.

TABLE 16 NUTRIENTS REMOVED IN GRAIN AND STRAW (Alberta Farm Guide, 1976)

Crop	Yield (t/ha)	Nutrients Removed (kg/ha)		
		N	P	K
Wheat	2.7	95.2	13.4	51.5
Barley	3.2	100.8	12.3	51.5
Oats	3.2	112.0	14.6	71.7
Grass	6.7	96.3	16.8	138.9
Alfalfa	9.0	277.8	19.0	159.0
Corn	13.4	155.7	29.1	117.6
Potatoes	33.6	252.0	28.0	302.4

TABLE 17 WATER USE BY CROPS (Korven and Randall, 1975)

Crop	Water use (mm)			
	Irrigation requirement		Consumptive use	
	S. Alta.	S. Sask.	S. Alta	S. Sask.
Alfalfa	40	51	66	66
Alfalfa + Bromegrass		45		61
Pasture grass	30		61	
Soft wheat	25		48	
Hard wheat	25	33	45	53
Oats	23		40	
Barley	25	33	40	48
Flax	13	38		
Corn	20		51	

Consumptive use: rainfall + irrigation to meet crop requirement
Southern Alberta: 11 years' data (1950-61); Sonmor (1963)
Southern Saskatchewan: 5 years' data; Pohjakas _et al_. (1967)

To assist in irrigation planning and to determine maximum water requirements for crops, soil moisture deficit maps have been developed for Canada (Sly, 1977). Assumptions made in developing these maps are:

a) May to September was selected as the growing period for crops on a Canada-wide basis.

b) Water content of the soil at the beginning of the season was assumed to be field capacity. As this assumption may not always hold true in semiarid areas, additional water may be required.

c) Consumptive water use by the crop is equal to the potential evapotranspiration, defined as the maximum quantity of water capable of being lost as water vapour, in a given climate, by vegetation that is adequately supplied with water.

Figure 15 is a map of Canada showing the seasonal water requirements in areas where 10 cm of soil moisture storage is available and the probability of rainfall occurrence is 50%. Detailed information for design purposes should be obtained from the reference source.

The greatest potential response to irrigation occurs in the southern prairies and the interior valleys of British Columbia (Oosterveld and Nicholaichuk, 1983). Production can be increased by up to 400% through irrigation. On the prairies, the limitation to development of irrigation systems is regional water storage. In Ontario, supplemental irrigation is economically attractive, providing water is available locally. In the most humid portions of Canada, the five eastern provinces, irrigation development is generally limited to specialty and fruit and vegetable crops where a small increase in yield can justify the costs of irrigation equipment.

Tanner (1974) maintains that maximum yield is associated with maximum transpiration. Maximum transpiration can be approached by providing irrigation that makes up the deficit between precipitation and potential evapotranspiration. Computerized models have been developed to indicate optimum irrigation requirements. Computerized budgeting techniques are available to optimize water applications for crop growth (Irrigation Scheduling Conference, 1981).

6.3 Crop Tolerance Factors

Excessive wastewater and sludge application may disrupt crop production. This may be reflected by reduced growth, delayed maturity, lodging and reduced crop quality. Several factors to be considered prior to applying wastewater and sludge are crop tolerance to nutrients, heavy metals, excess water and salinity.

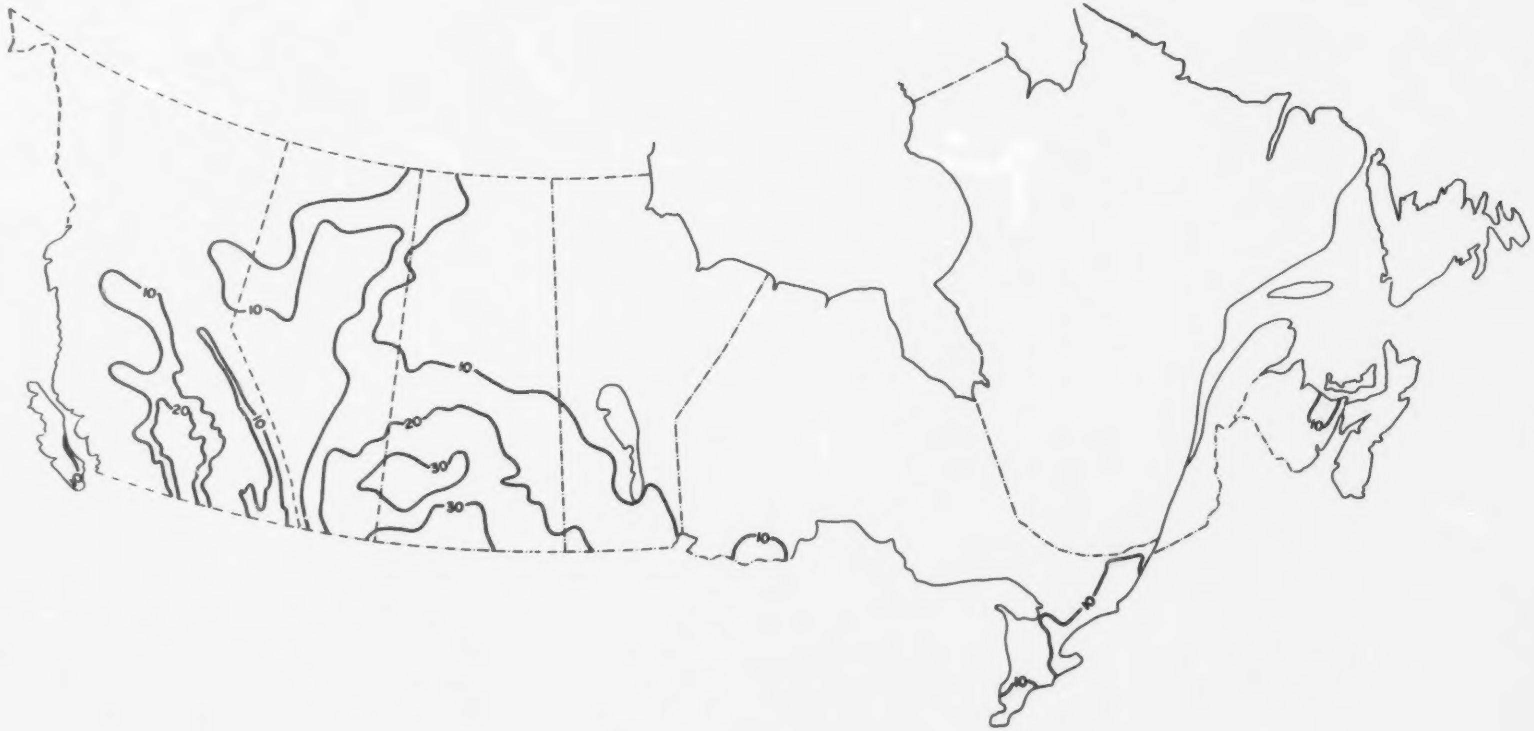

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FIGURE 15 IRRIGATION WATER REQUIREMENTS (cm) IN CANADA FOR 50% RAINFALL PROBABILITY AND 10 cm (good) SOIL MOISTURE STORAGE (Sly, 1977)

6.3.1 Nutrients. Effects of excess nutrients differ from problems due to salts or heavy metals because large amounts of nutrients are needed for crop growth. Most of the problems associated with excess and untimely fertilizer application are centred around nitrogen. Overabundances of N can cause crop lodging and excessive vegetative growth. For example, excessive nitrogen results in excessive foliage growth and decreased potato production. It can also decrease the sugar content in sugarbeets. Nitrogen loadings in sludge and wastewater applications should match the nitrogen requirement of the crop to be grown.

Excess nitrates in forage crops may result in production of nitrous oxide gases following ensiling. These gases can be deadly to humans and farm animals in enclosed areas. More commonly, the excess nitrates present a toxicity problem when ingested by animals. Nitrate may be converted to nitrite which, following absorption, may react with hemoglobin to cause methemoglobinemia or cyanosis. This condition results in inability of the hemoglobin to transport oxygen and often results in suffocation of the animals. Nitrate accumulation in plant tissues varies with plant type, growing conditions, stage of growth and fertilization.

Modifications to counteract the effect of excessive and untimely applications of N have included thinning the crops, stressing them between irrigation periods and diluting effluent with normal irrigation water. Crops that have a low tendency to accumulate nitrates can be selected. For example, Ryan et al. (1972) showed that bromegrass and/or reed canary grass exhibited less tendancy to accumulate nitrate than orchardgrass and tall fescue.

Excess phosphorus is not considered to be toxic to plants but may induce deficiencies of Ca, Zn, Fe or Mn. These trace element deficiencies can be corrected by the addition of chemical fertilizers.

Potassium is generally nontoxic to plants or plant consumers. It is generally present at low or moderate concentrations in treated wastewater and sludge, and therefore should not cause toxicity problems although nutrient imbalance may occur. A combination of high nitrate levels and potassium has been associated with reduced magnesium uptake in forages and subsequent magnesium deficiency of lactating cows and sheep.

6.3.2 Heavy Metals. When plants absorb excessive amounts of heavy metals, they can be injured and their growth reduced. Severe phytotoxicity may kill plants. Of the elements commonly found in organic wastes, only Zn, Cu, and Ni are likely to cause phytotoxicity following improper management of wastewater or sludge. Because pH strongly affects soil sorption of these metals, it has a dominant effect on their solubilities (similar to that illustrated for Cd in Figure 16) and phytotoxicities. Excess Cu and Ni cause injury to plant roots, and Cu and Ni toxicity symptoms are generally expressed as yellow (chlorotic) young leaves due to induced Fe-deficiency. Zinc is translocated more freely to the leaves than Cu and Ni. Although Zn can injure roots and induce chlorosis, its toxicity is usually manifested through injury to older leaves and reduction of plant growth through interference with biological processes.

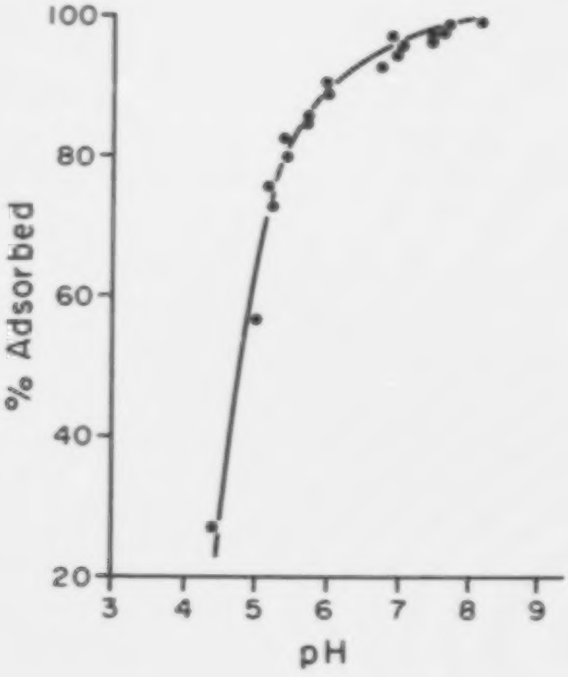

FIGURE 16 SOIL ADSORPTION OF Cd AS A FUNCTION OF SOIL pH

Boron toxicity has resulted when sensitive crops are grown on soils amended with high rates of refuse compost (Purves and Mackenzie, 1974) or when boron concentrations in wastewater exceed desirable limits.

Most vegetable crops and legumes are relatively sensitive to metals in acidic soils. Tolerances of crops to metals (based on greenhouse studies with sludge) are given in Table 18 (Chaney and Giordano, 1977; Foy et al., 1978).

The U.S.D.A. (1978) has developed recommendations for maximum application of Zn, Cu and Ni so that phytotoxicity will only occur under low pH conditions. The landowner is advised to add limestone to maintain a pH $\geq$6.5 to prevent toxicity.

TABLE 18 RELATIVE SENSITIVITY OF CROPS TO HEAVY METALS (Chaney, 1982)

Very sensitive	Sensitive	Tolerant	Very tolerant
Ladino clover	Mustard	Oat	Corn
Alsike clover	Zigzag, Red Kura and crimson clover	Orchardgrass	Sundangrass
Crownvetch	Alfalfa	Japanese bromegrass	Smooth bromegrass
'Arc' alfalfa	Blue lupin	Switchgrass	'Merlin' red fescue
White sweet clover	Birdsfoot trefoil	Red top	
Yellow sweet clover	Hairy vetch	Buffalograss	
Weeping lovegrass	Soybean	Tall fescue	
Lehman lovegrass	Timothy	Red fescue	
Deertongue	Colonial bentgrass	Kentucky bluegrass	
	Perennial ryegrass		
	Creeping bentgrass		

The heavy metal of most concern is cadmium (Cd). Cadmium is highly toxic and has no known biological function. During the past decade concern over Cd in the environment has increased because it has been linked to renal tubal damage and pulmonary emphysema in humans. Cd accumulates in the liver and kidneys and the possible health hazard to humans and animals from elevated levels in plants has created much more concern than its toxicity to plants. The uptake of cadmium differs greatly from crop to crop as indicated in Figure 17; however, phytotoxicity occurs at concentrations several times higher than those of concern in human and animal diets. Consequently, if effluent and sludges contain significant levels of cadmium, loading rates must be regulated to limit its entry into the food chain.

6.3.3 **Excess Water.** Excess water in the root zone can reduce crop growth and affect field operations. The benefits to be derived from removal of excess water were summarized by Van't Woudt and Hagan (1957). Drainage usually allows greater and earlier

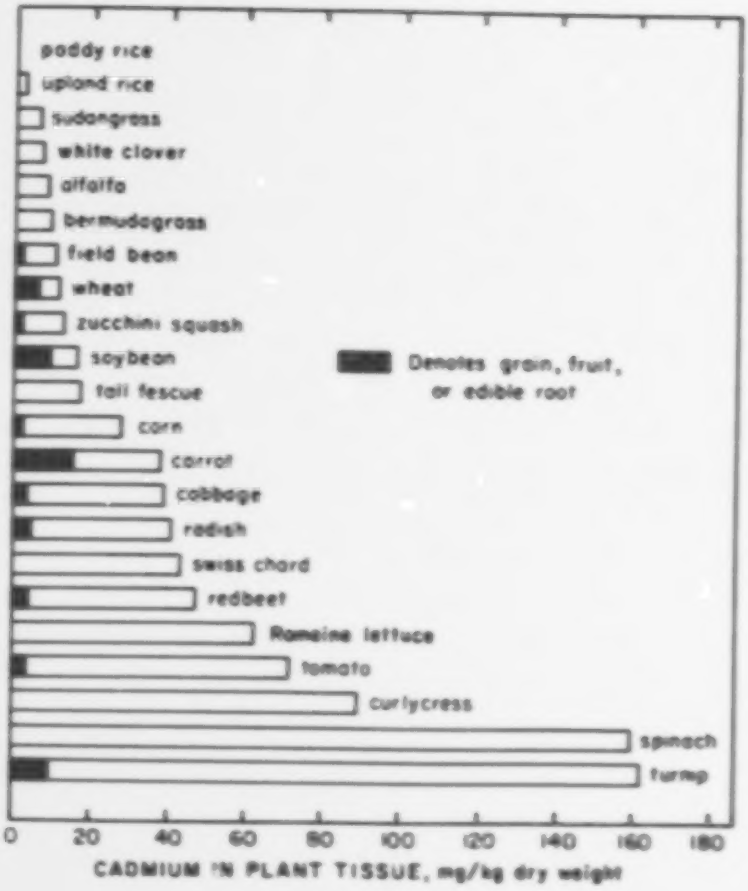

FIGURE 17 DIFFERENCES IN Cd ACCUMULATION BY CROPS

Crops were grown on calcareous Domino silt loam soil amended with 1% dry weight basis of a Cd-enriched sewage sludge (1000 ppm Cd) such that the amended soil contained 10 ppm Cd. Where a plant tissue other than leaves is normally eaten, its Cd concentration is shown in the black bar; foliar Cd for each plant is the full open bar (turnip leaves = 163 ppm Cd). (From Chaney and Hornick, 1978, based on Bingham et al., 1975, 1976a, 1976b) crop growth, which is an advantage for wastewater application if the objective is to utilize wastewater, and increases the amount of water that can be applied without reducing crop yield.

Where excess water may be a problem, crops tolerant to flooding should be chosen. Among the grasses, reed canary grass, ryegrasses and tall fescue have high moisture tolerances. In wetlands, catails, Typha ssp. and bulrushes Scirpus ssp. can be utilized.

6.3.4 Salt. Tolerance of crops to salinity is generally expressed in terms of electrical conductivity of the saturation extract of the root zone soil at which a reduction in crop yield is experienced. The percent reduction is calculated compared to yield under nonsaline conditions. Thus, the salt tolerance is a relative value based on cultural conditions under which the crop is grown. Absolute tolerances that reflect inherent physiological responses by plants cannot be determined because many interactions between plant, soil water and environmental factors influence the plant's ability to tolerate salt.

To minimize the ambiguity of interpreting results from non-uniform salinity profiles, most of the data on plant tolerance to salinity have been obtained from experiments in artificially salinized field plots where salinity was maintained essentially uniform with depth throughout the root zone by irrigation with saline waters at very high leaching fractions. Moss and Hoffman (1977) of the U.S. Salinity Laboratory summarized the worldwide literature on the subject of crop salt tolerance. They reported that, in general, crop yield was not decreased significantly until a threshold salinity level was exceeded and that yield decreased linearly as salinity increased beyond the threshold. This relationship is expressed by:

$$Y = 100 - (EC_e - A)B$$

where Y is the relative yield (%), EC_e is the mean soil salinity expressed as the conductivity of the saturation extract, A is the threshold salinity level and B is the slope of yield depression versus increased salinity. If the salinity is lower than the threshold value, the yield remains at 100%. Based on this concept, three divisions are made corresponding to three crop tolerance groups: moderately sensitive, moderately tolerant and tolerant.

A table of salt-tolerances for major crops grown on the prairies was prepared using this format and available values (Table 19). The limitations of the salt tolerance data presented in Table 19 should be clearly understood. The data were collected under

TABLE 19 SALT TOLERANCE OF MAJOR CROPS GROWN ON THE CANADIAN PRAIRIES

Moderately Sensitive				Moderately Tolerant				Tolerant			
Crop	A[1]	B[2]	Max.[3] EC_e	Crop	A	B	Max. EC_e	Crop	A	B	Max. EC_e
Alfalfa	2.0	7.3	15.5	Barley (forage)	6.0	7.1	20	Barley (Grain)[4]	8.0	5.0	28
				Bromegrass	-	-	-	Fairway wheatgrass	7.5	6.9	22
Corn (Forage)	1.8	7.4	15.5	Reed canary grass	-	-	-	Tall wheatgrass	7.5	4.2	31.5
Corn (grain)	1.7	12	10	Oat	-	-	-				
Flax	1.7	12	10	Rapeseed	-	-	-	Sugar beet[5]	7.0	5.9	24
								Russian wild rye	-	-	-
				Birdsfoot trefoil	-	-	-	Altai wild rye	-	-	-
				Wheat[4]	6.0	7.1	20				
				Crested wheatgrass	3.5	4.0	28.5				
				Slender wheatgrass	-	-	-				

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[1] Salinity (expressed as EC_e in dS/m) at initial yield decline (threshold)

[2] Yield decrease (%) per unit increase in salinity beyond threshold

[3] Maximum EC_e: maximum salinity that plants can tolerate (dS/m)

[4] Less tolerant during emergence and seedling stage. EC_e should not exceed 4 to 5 dS/m

[5] Sensitive during germination. EC_e should not exceed 3 dS/m

experimental conditions where salinity was maintained uniformly throughout the soil profile. Adequate (although saline) water was maintained in the profile at all times. Applying these data to field conditions where salinity distribution is not uniform requires a knowledge of plant response to salinity that varies with depth. Researchers in the Canadian prairies have found that the yield reduction due to salinity is generally underestimated.

Leaching is required to prevent the buildup of salts when using poor quality irrigation water. The fraction of applied water that drains below the root zone is commonly referred to as the leaching fraction (LF). Generally, natural drainage that allows 15% of the applied water to pass through the root zone is adequate. The minimum leaching requirement, LR_{min} (the minimum amount of leaching needed to control salt in the root zone within the maximum salinity that plants can tolerate) is calculated with the equation:

$$LR_{min} = \frac{EC_{iw}}{(2)\,(\text{Max. } EC_e)}$$

where EC_{iw} is the salinity of the irrigation water and Max. EC_e is the maximum salinity that plants can tolerate. The factor 2 is used to convert the salt concentration of the saturation extract to the concentration of the soil solution at field capacity.

Yield decrease to be expected due to salinity of irrigation water has been calculated for alfalfa (Table 20), wheat (Table 21) and barley (Table 22) based on uniform salinity throughout the soil profile and the salt tolerance data presented in Table 19.

Based on the foregoing analyses, it is believed that water having an EC value of less than 3 dS/m can be used for irrigation of the major crops grown on the Canadian prairies (except for some sensitive crops) at or near 85 to 100% productivity. Although waters containing higher than 3 dS/m of salt can be used successfully to irrigate more salt-tolerant crops, an important consideration is the problem that may arise if a farmer changes from a salt-tolerant crop to a less tolerant crop to meet changing economic conditions. If a permit for irrigation with wastewater is to be issued, it would be advisable to restrict the EC value to less than 3 dS/m.

The major irrigated crop grown on the prairies is alfalfa. The amount of water needed to grow alfalfa under irrigation while satisfying a leaching fraction of 0.15 in the area of southern Alberta and Saskatchewan is about 70 cm. With effective precipitation of 18 cm, alfalfa requires an additional 52 cm of irrigation water to

TABLE 20 ESTIMATED ALFALFA YIELD REDUCTION (%) DUE TO SALINE IRRIGATION WATER

Salinity of irrigation water (dS/m)	Minimum leaching requirement LR_{min}	Leaching fraction (LF)			
		0.1	0.2	0.3	0.4
1.0	0.04	0	0	0	0
2.0	0.07	8	3	0	0
3.0	0.10	19	12	7	5
4.0	0.13	-*	20	15	12
5.0	0.16	-	29	22	18

* $LF<LR_{min}$ not recommended

TABLE 21 ESTIMATED WHEAT YIELD REDUCTION (%) DUE TO SALINE IRRIGATION WATER

Salinity of irrigation water (dS/m)	Minimum leaching requirement LR_{min}	Leaching fraction (LF)		
		0.1	0.2	0.3
5	0.13	0	0	0
6	0.15	9	0	0
7	0.18	17	7	2
8	0.20	26	14	9
9	0.23	-*	21	15

* $LF<LR_{min}$ not recommended

TABLE 22 ESTIMATED BARLEY YIELD REDUCTION (%) DUE TO SALINE IRRIGATION WATER

Salinity of irrigation water (dS/m)	Minimum leaching requirement LR_{min}	Leaching fraction (LF)			
		0.1	0.2	0.3	0.4
6	0.13	7	0	0	0
7	0.15	-*	2	0	0
8	0.18	-	8	0	0
9	0.20	-	14	5	1
10	0.23	-	20	10	5

* $LF<LR_{min}$ not recommended

maintain yields near 12 tonnes/ha. The 18 cm of precipitation is considered to dilute the irrigation water by 30%.

6.4 Crop Quality

6.4.1 Nutrients. Information about crop quality following application of treated wastewater and sludge in Canada is limited. The chemical compositions of wastewater-irrigated forages have been examined in studies at Swift Current (see Appendix D) and Taber (Bole and Bell, 1978). Quality of cereals and forages following sludge application has been monitored at Edmonton, Calgary, Guelph and Burlington.

The nitrogen and phosphorus of forages produced with wastewater irrigation were at least as high as those of forages produced with conventional irrigation at Swift Current (Table 23). Considerable variation occurred in the levels of these nutrients in the alfalfa, which reflects time of cutting as well as management practices.

TABLE 23 COMPOSITION OF IRRIGATED ALFALFA AT SWIFT CURRENT (1973-1981)

	Effluent irrigated alfalfa	Creek water irrigated alfalfa
% Nitrogen	2.3 - 4.1	2.3 - 3.8
% Phosphorus	0.19 - 0.36	0.18 - 0.30
% Crude Protein	14.8 - 25.4	14.4 - 23.9

In another study at Taber (Bole and Bell, 1978), various forage crops were subjected to wastewater irrigation with and without fertilizer. The nitrogen content of alfalfa was double that of grasses with the unfertilized wastewater treatment and considerably greater than that of grasses with the other treatments. Nitrogen uptake by all forages exceeded that applied in wastewater and fertilizer (Table 24). Phosphorus application in the wastewater or as fertilizer exceeded plant uptake. The P content of forages (0.32 to 0.34%) was unaffected by the added P fertilizer; thus P uptake was determined by the yield.

In the Taber study, alfalfa had the highest protein content. Reed canary grass had a higher protein content than other grasses (Table 25). Added nitrogen and phosphorus fertilizer did not affect the protein contents of the wastewater-irrigated forages.

TABLE 24 FOUR-YEAR MEAN UPTAKE OF N BY EFFLUENT IRRIGATED FORAGES (Bole and Bell, 1978).

Treatment	Applied N	Forages				
		Alfalfa	Reed canary grass	Bromegrass	Altai wild rye	Tall wheatgrass
	kg/ha					
Wastewater	97	270	124	123	106	100
Wastewater with added fertilizer	153	282	193	186	167	145

TABLE 25 AVERAGE PROTEIN CONTENT OF FORAGES (Bole and Bell, 1978)

	Alfalfa		Reed canary grass		Bromegrass		Altai wild rye		Tall wheatgrass	
	1 cut	2 cut	1 cut	2 cut	1 cut	2cut	1 cut	2 cut	1 cut	2 cut
	%									
Wastewater	21.6	18.9	15.9	12.5	13.4	13.4	11.8	11.3	12.3	12.0
Wastewater with added fertilizer	21.9	17.0	17.6	12.5	15.2	13.1	13.8	11.9	13.0	11.9

As would be expected in fertilizer trials, the N (indicator of protein) and P contents (Table 26) increased with the application of sludge in both alfalfa and barley (McCoy, 1977). The only exception was the P content of the barley grain which tended to decrease with increased sludge application. The levels of nutrients in the forage and grain were not considered to be hazardous.

6.4.2 **Heavy Metals.** Heavy metal uptake by crops after sludge application has been studied by McCoy (1977), Webber et al. (1980), Soon et al. (1978) and Lutwick and Graveland (1983). These studies were located at Guelph and Burlington in eastern Canada and at Calgary and Edmonton in western Canada.

In western Canada, test plots were established to determine the effect of sewage sludge application on the yield and chemical composition of several agricultural crops. Utilizing randomized block designs, sewage sludge was applied at rates of 9.1, 13.7

TABLE 26 CROP COMPOSITION FOLLOWING SLUDGE APPLICATION (McCoy, 1977)

Crop	Sludge application (t/ha)	N(%)		P(%)	
		1st cut	2nd cut	1st cut	2nd cut
Alfalfa	0	2.9	3.2	0.2	0.2
	7.5	3.4	3.3	0.2	0.2
	10	3.8	3.8	0.3	0.3
	20	4.1	3.0	0.3	0.3
		Grain	Straw	Grain	Straw
Barley	0	2.2	0.7	0.3	0.04
	9.1	2.5	0.9	0.2	0.04
	13.7	2.5	0.8	0.2	0.03
	22.9	2.6	1.0	0.2	0.04

and 22.9 t/ha at Calgary and at rates of 7.5, 10 and 20 t/ha at Edmonton. Soils, sludge and plant materials were sampled and analysed for the constituents listed in Tables 26 and 27.

Results obtained from one year of study at Calgary (McCoy, 1977) on a dark brown soil indicated a significant increase in the Pb content of barley straw (Table 28), but no effect on the Zn, Cu, Mn, Fe, Ni, or Cd content of grain. Zinc concentrations were significantly higher and Pb was significantly lower in the grain portion than in the straw of barley plants at maturity.

In the Edmonton study, sludge applied in 1978 on black soils at the rate of 20 t/ha resulted in yield increases in the first and second cuts of 1.2 and 2.5 t/ha of alfalfa, respectively (Table 29). Zinc and Mg increased in the first cut but not in the second. No changes in Ni, Cd, Pb, Cu, Ca, K and Fe occurred in either cuts (Lutwick and Graveland, 1983).

In both the Edmonton and the Calgary studies, further monitoring is required to determine long-term effects of sludge application on forage quality.

In eastern Canada, sludge application studies have been conducted at various sites, including Guelph, Burlington and the Halton region, and with a variety of field and vegetable crops.

A lysimeter study at Burlington indicated that large differences in heavy metal concentrations occur between crops (Webber and Monks, 1981). Buckwheat and Swiss chard exhibited the largest concentrations followed by soybean and romaine lettuce,

TABLE 27 COMPOSITION OF BARLEY STRAW FOLLOWING SLUDGE APPLICATION AT CALGARY (McCoy, 1977)

	No Sludge	Sludge at 9.1 t/ha	Sludge at 13.7 t/ha	Sludge at 22.9 t/ha
	mg/kg			
Zn	10	21	15	23
Cu	3.7	4.0	2.7	3.0
Mn	20	14	18	26
Fe	37	47	42	55
Pb	0.50*	0.62_a	0.67_a	0.70_a
Ni	0.2	0.3	0.2	0.5
Cd	< 0.05	< 0.05	< 0.05	< 0.05

* Within rows, means followed by the same letter or no letter do not differ significantly ($P = 0.05$) by Duncan's New Multiple Range Test.

TABLE 28 YIELD AND COMPOSITION OF BARLEY GRAIN FOLLOWING SLUDGE APPLICATION AT CALGARY (McCoy, 1977)

	No Sludge	Sludge at 9.1 t/ha	Sludge at 13.7 t/ha	Sludge at 22.9 t/ha
	mg/kg			
Zn	43	49	42	47
Cu	6.0	6.0	5.2	5.2
Mn	15	14	13	14
Fe	67	42	47	40
Pb	0.17	0.20	0.23	0.23
Ni	0.18	0.09	0.09	0.05
Cd	< 0.05	< 0.05	< 0.05	< 0.05
	t/ha			
Yield	1.30	1.12	1.60	1.21

TABLE 29 ALFALFA COMPOSITION AND YIELD FOLLOWING SLUDGE APPLICATION AT EDMONTON (McCoy, 1977)

	1st cut				2nd cut			
	Sludge				Sludge			
Constitutent	0	7.5 t/ha	10 t/ha	20 t/ha	0	7.5 t/ha	10 t/ha	20 t/ha
	mg/kg							
Ni	3.15	3.59	3.37	2.23	2.27	1.72	2.27	2.05
Cd	0.37	0.42	0.37	0.37	<0.25	<0.26	<0.29	<0.22
Pb	<1.25	<0.17	<0.85	<0.92	<1.14	<0.87	<0.88	<0.78
Cu	20.7	12.7	11.6	12.5	12.9	9.9	9.6	10.3
Zn	21.5_a*	40.4_b	46.0_b	43.1_b	24.2	25.3	29.9	29.7
Mn	25.0	27.9	22.9	22.0	40.7_b	22.0_a	30.3_{ab}	24.2_a
Fe	244	183	162	162	278	201	265	214
	%							
K	1.95	1.68	1.82	2.32	2.12	2.07	1.58	19800
	t/ha							
Yield	1.8_a	2.1_a	3.4_b	3.0_b	2.4_a	3.9_a	4.6_a	4.9_b

* Within rows and cuts, means followed by the same letter or no letter do not differ significantly ($P = 0.05$) by Duncan's New Multiple Range Test.

and wheat and orchard grass. Sludge treatment generally increased the Cd, Zn and Cu concentrations in crops but there was no consistent effect on the Ni, Pb and Cr concentrations.

A lysimeter study at Burlington indicated that large differences in heavy metal concentrations occur between crops (Webber and Monks, 1981). Buckwheat and Swiss chard exhibited the largest concentrations followed by soybean and romaine lettuce, and wheat and orchard grass. Sludge treatment generally increased the Cd, Zn and Cu concentrations in crops but there was no consistent effect on the Ni, Pb and Cr concentrations.

Lysimeter studies at Burlington and field studies at Guelph indicated that orchard grass, bromegrass, wheat and corn yields following sludge applications greatly in excess of recommended rates were equal to or larger than yields with commercial fertilizer (Webber, et al., 1980). In general, heavy metal concentrations in the crops were not greatly increased by sludge application. Similar heavy metal results were observed for field crop materials (mainly corn leaves) taken from old sludge application sites in Ontario, some of which had received large sludge applications (Webber, et al., 1983).

Yields of winter wheat, oats and corn grain grown on farms in Halton County, Ontario, following sludge application at the recommended rate for Ontario (i.e., 135 kg/ha $(NH_4 + NO_3) - N$ in sludge) were equivalent to yields with commercial fertilizer (Municipality of Halton, 1981). There was no significant increase in heavy metal concentrations in any of the crops.

It is apparent from the studies conducted in western and eastern Canada that sludge application at the low rates recommended by existing guidelines (Alberta Environment, 1982 and OMAF/OMOE, 1981) is unlikely to increase the heavy metal concentrations in crops significantly or to cause deleterious crop or food chain effects.

6.4.3 **Toxic Organics.** Although much research has been conducted on insecticides, fungicides and herbicides, insufficient information is available to assess the food chain risk of waste-borne toxic organic compounds. Most are sparingly soluble in water and accumulate in sludge during wastewater treatment. Consequently, there is concern that they may occur in plant materials grown on sludge treated land.

Limited evidence indicates that halogenated hydrocarbons may be accumulated, particularly in root vegetables (Chaney, 1982). Carrots have a lipid rich epidermal layer and are more effective accumulators than sugar beets, onions, turnips and rutabagas. A study of sludge application sites in Ontario indicated statistically significant but small increases in the polychlorinated biphenyl (PCB) concentrations in soils but no increase in PCB concentrations in corn leaf materials grown on the sludge treated land (Webber et al., 1983).

Systemic pesticides applied to the soil or plant foliage are absorbed and translocated throughout plants and act to protect them. These toxic organics are water soluble and are unlikely to be present at significant concentrations in sludges. Where they occur in treated wastewaters, a waiting period as indicated by instructions for their use on agricultural land should be observed prior to harvesting the crop.

6.4.4 Microbiology. Microbiological studies designed to assess the survival characteristics of fecal coliforms on crops irrigated with municipal effluent have been conducted by Biederbeck (1982) at Swift Current, and Bell and Bole (1976) at Lethbridge. This group of organisms is generally accepted as an indicator of the presence of other pathogenic organisms.

At Lethbridge, Bell (1976) concluded that fecal coliforms on alfalfa plants irrigated with sewage lagoon effluent were completely destroyed by exposure to 10 hours bright sunlight. No decrease in numbers was observed under cool, damp, overcast conditions. When raw sewage was applied, exposure to 10 hours bright sunlight was adequate to destroy all the fecal coliforms on alfalfa. In the event that sewage treatment failures such as lagoon short-circuiting occurred while alfalfa was being irrigated with wastewater in the semiarid prairie region, livestock would be adequately protected from possible salmonella and enteropathogenic Escherischia coli infection if at least two sunny days elapsed between the cessation of wastewater irrigation and the consumption of the forage.

In a similar study dealing with reed canary grass (Bell and Bole, 1976), exposure to 50 hours bright sunlight under semiarid prairie conditions was sufficient to destroy virtually all fecal coliforms present on the grass after irrigation with sewage effluent containing about 3.2×10^4 fecal coliforms/100 mL. This was considerably longer than the 10 hours previously shown to be adequate to eliminate fecal coliforms from alfalfa. The difference between species is due to the presence of leaf sheaths on the grass in which effluent could collect and be protected from the bacteriocidal effects of bright sunlight.

As the number and size of wastewater irrigation projects in western Canada has increased, demand has been growing for use of wastewater irrigation in the production of nonforage crops. The potential health hazards were investigated by Biederbeck (1980,

1982) at Swift Current with cereal and oilseed crops. To simulate the worst possible sanitary situation, raw sewage was sprayed onto microplots of canola, wheat and oats two weeks before swathing and the persistence of fecal coliforms was determined by periodically analysing the plant material. Immediately after irrigation the plants retained large numbers of fecal coliforms, but the bacteria were rapidly destroyed by exposure to bright sunlight and the desiccating effect of windy, warm weather (Table 30). The greater persistence of coliforms on cereal stocks than on heads was caused by the leaf sheaths trapping and protecting the sewage from sunlight and desiccation.

TABLE 30 FECAL COLIFORM DIE-OFF ON WHEAT IRRIGATED WITH RAW SEWAGE DURING FINE WEATHER

Hours after Irrigation	Fecal coliforms (mean number/g dry weight)* on	
	Heads	Stems and leaves
0	79 000	111 000
3	438	4 350
6	46	1 800
12	5	551
24	1	403
30	2	44

* Means counts for three consecutive experiments.

The study also indicated that fecal coliforms on grain crops can be effectively eliminated in the absence of bright sunlight as long as the weather is dry and warm. The following guideline was provided: "To ensure complete elimination of fecal coliforms, effluent-irrigated small grains and oilseeds should be exposed to a minimum of 10 hours of bright sunlight or 2 days of overcast but dry weather between the end of irrigation and the start of harvest". As the water requirements of cereals greatly decrease during ripening, irrigation is not necessary close to harvest and the recommended decontamination conditions are easily met. Thus, small grains and oilseeds can be produced safely under spray irrigation with treated municipal wastewater.

Experiments with raw sewage in 1979 indicated that corn is definitely unsuitable for wastewater irrigation (Biederbeck, 1980). Extensive survival and rapid growth of fecal coliforms within the husks and leaf sheaths pose serious health hazards.

In 1980 corn was irrigated on a field scale with effluent from a secondary treatment lagoon at Swift Current. While coliforms on exposed portions of corn leaves were destroyed as rapidly as those on wheat, oats and canola, the fecal coliforms entrapped within the leaf sheaths and husks were protected from the killing effects of bright sunlight, rapid drying and even night frost. Six hours after irrigation, numbers of coliforms in effluent retained in leaf sheaths and husks were 60 000/100 mL, about 2000 times greater than on exposed leaves.

Decontamination of corn was investigated at Swift Current and it was shown that effluent-irrigated corn can be decontaminated through ensiling. Fecal coliorms were reduced from about 3 x 10^6/g at harvest to 0/g in mature silage. Although ensilage will produce a safe feed, the risks of infection to farmers during cutting, chopping and transportation of corn prior to ensiling are too great to sanction spray irrigation of corn with wastewater. To avoid health risks wastewater irrigation systems for corn must employ gravity flow rather than spray systems (Biederbeck, 1982).

A study using digested sludge as a medium for growing tomatoes indicated it to be free of fecal coliforms and practically free of total coliforms (Hwang *et al.*, 1982). Essentially, the sludge was found to be an adequate substrate for microbiological development of viable bacteria and fungi similar to population levels found in fertile soils. Since sludges are usually added to and incorporated into the soil, they generally do not constitute a microbiological hazard to the growing plant.

Research on pathogens in relation to land application of sewage sludge was undertaken as a part of the Canada-Ontario Agreement on Great Lakes Water Quality research program. Studies of microbial pathogens were undertaken at the University of Guelph (Bates *et al.*, 1978). Indicator microorganisms, and human pathogens such as members of the genera *Salmonella* and *Shigella* were monitored in anaerobically digested sludges, in runoff waters from field experimental plots receiving surface applications of liquid sludge to supply 200 and 800 kg N/ha each November, January and May, and on plant materials harvested from the field experimental plots. Between May, 1973 and March, 1976, *Salmonella* species were detected in 20 of 54 sludge samples. Runoff from sludge-treated field plots was not consistently higher in fecal coliforms or fecal streptococci than the plots receiving chemical fertilizers. *Salmonella* were detected in one of 484 runoff samples, on one of 96 grass samples and on four of 111 corn samples studied. *Shigella* were not detected in any of the samples. It was concluded that "if vegetables are not grown and animals are not grazed on areas receiving sludge, and if reasonable care is exercised in spreading, sludge does not pose a serious health hazard through the crops grown".

Virus isolation rates for anaerobically digested sludges sampled from five sewage treatment plants during 1973 to 1975 were 1/111, 4/101, and 16/101 (Subrahmanyan, 1977). The isolates included 18 reoviruses for which no specific pathogenic role has been identified, and three unidentified enteroviruses. It was concluded that spreading digested sludge on land probably poses a low-level health hazard. However, this conclusion was qualified by adding that virus prevalence in the community was low during the survey period and that practical detection methods are not available for the important agents responsible for hepatitis and gastroenteritis.

Ascaris, Toxocara, Trichuris and hookworm ova were recovered frequently and Taenia, Hymenolepis and Toxascaris ova were recovered only rarely from anaerobically digested sludges land applied in Ontario (Graham, 1981). Undeveloped Ascaris and Toxocara were recovered from a recently sludged field and fully developed Ascaris were recovered from a field where sludge had been applied several weeks previously. Only a few non-viable Ascaris were recovered from a field that had received sludge one and one-half years previously. Evidence indicated that Ascaris and Toxocara ova may survive on pasture land for several years and on bare soil for one year but they probably survive only a few weeks when sludge is incorporated into the soil. Taenia ova probably survive only a few weeks in sludge applied to well-drained pasture land during hot dry weather, but some may survive more than one month when sludge is applied during cool, wet weather.

Graham (1981) recommended that cattle not be allowed to graze on freshly sludged land due to the possible presence of T. saginata. The delay between sludge application and grazing was not identified; however, considering the small number of ova recovered from Ontario sludges, the fact that they die off in soil, and that no outbreaks have been reported following application of digested sludges, a delay of two months would appear to be adequate. Graham also recommended that vegetables for human consumption not be grown within one year of sludge application.

6.5 Crop Alternatives

The following crops have been grown on land treated with wastewater or sludge:

a) small grains;
b) row crops;
c) perennial forages;
d) forests;
e) fruit crops; and
f) vegetables.

These alternatives are discussed in detail below.

6.5.1 **Small Grains.** A high degree of management is required at all stages of small grain crop production, including annual land preparation, seeding, weed control and harvesting. Nutrient and water removal by small grain crops are minimal due to the short period of active growth.

Small grains include wheat, barley and oats. These crops provide a means of cost recovery for the land application system; however, they are not very tolerant of excess water and nutrients, and stem weakness or breakage results in "lodging" when excess nitrogen is applied. Because of the need to limit nutrient and water application, relatively large areas of land are required for irrigation and large reservoirs are needed for off-season wastewater storage. Small grains may be used successfully as a nurse crop for perennial crop establishment.

Some varieties adapted to western Canada that have "lodging" resistance are as follows:

Crop	Variety
Oats	Fidler, Randon Cascade
Soft white wheat	Fielder
Bread wheat	Columbus, Napayo, Sinton
Durum wheat	Coulter, Macoun
Barley, 6-row	Klondike, Melvin, Galt
Barley, 2-row	Harrington, Norbert

It is important to consult local agricultural authorities for recommended varieties.

6.5.2 **Row Crops.** Row crops include corn, soybeans, sunflowers and sugar beets. These crops, like small grains, provide a means of cost recovery for the land application system. Water and nutrient removal by row crops is limited to the time between crop establishment and maturity. Row crops do not lend themselves to overland flow irrigation systems because the spaces between the rows may act as conduits.

Row crops offer some advantages over small grains. They are adaptable to on-site vehicular traffic which makes field operations such as weed control and fertilizer application possible. Crops such as corn for silage provide an opportunity for maximum nutrient removal by harvesting the entire above-ground portion.

It is important to note that corn is not recommended for spray irrigation due to the health hazards discussed in Section 6.4.4.

6.5.3 Perennial Forage. Perennial forages include legumes and grasses. They are most frequently used as cover crops for wastewater irrigation systems and may be managed by frequent mowing or cutting for hay, green feed or silage to maximize growth. Forage crops offer the following advantages:

a) competitive with natural vegetation and weeds;
b) good utilization of plant nutrients;
c) tolerance to wet conditions;
d) relatively successful on poor soils;
e) excellent erosion control;
f) longer periods of active growth than small grains and row crops;
g) improve soil structure and enhance water transmission and soil aeration;
h) ability to withstand heavy vehicle traffic;
i) cold weather hardiness; and
j) ability to withstand grazing.

The long growing season results in high water consumption. As a result, land area and wastewater winter storage requirements are usually lower than those for small grains and row crops. Grasses such as reed canary, brome, timothy, fescue, perennial rye and orchard are frequently used crops. They are more tolerant than legumes of frequent flooding and heavy vehicle traffic. However, grasses are usually less palatable to livestock than legumes as feed. Legumes are suitable when the nitrogen content of wastewaters or sludge is relatively low. An effectively innoculated legume can make up the deficiency by symbiotic nitrogen fixation from the air. However, legumes are susceptible to winter killing due to ice smothering and soil heaving. Forage mixtures of legumes and grasses combine the benefits of both crops and create an easily manageable and marketable cover crop.

Irrigation of turf grasses with wastewater in parks, golf courses and recreational areas is gaining popularity. However, precautions are required to minimize health risks from pathogens and such irrigation projects are subject to local environmental regulations.

6.5.4 Forests. Forests have the potential for accepting relatively large volumes of wastewater and organic matter. A five-year study in the Kananaskis Valley in Alberta indicated the mean annual water deficit to be 200 mm (Graveland, 1980). Infiltration rates are typically quite high (15 cm/h or greater) because the high organic content of forest surface soils makes them very porous. The upper mineral soil is highly porous and is protected by vegetation and surface litter against the impact of water drops. The litter layer also furnishes food for organisms which permeate the soil and maintain conditions for water entry. The absence of heavy vehicle traffic and the thick surface litter prevent soil compaction and enhance infiltration rates.

Forests do not remove large quantities of nutrients, particularly nitrogen, from soil. Irrigation of lodge-pole pine (Pinus contorta) in Alberta with municipal wastewater that had a consistently low nutrient content resulted in no change in soil nutrient status after five years. Tree growth on the irrigated plot was 38% greater than on the non-irrigated plot. Although the natural uptake of nutrients compares with many agronomic crops, only a small percentage is removed from the area because nutrient-rich leaves, twigs, bark and roots are returned to the soil. Logging removes accumulated nutrients from the forest site but the amounts are low compared to the time required for tree growth.

6.5.5 **Fruit Tree Crops.** Very little information is available in Canada with respect to applying municipal wastewater and sludge to fruit tree crops. Generally, fruit tree crops can be trickle-irrigated to minimize health hazards and managed in a fashion so as to maximize nutrient utilization without causing delay in hardening of trees and winter injury.

Ontario sludge guidelines call for application in late fall (November) or up to three months before fruit harvest. Management of nutrient input must be monitored to prevent erratic growth that would impair fruit quality.

6.6 Benefits of Cover Crops

Several aesthetic and economic benefits are associated with land application systems. Vegetative cover has aesthetic value because the appearance of a waste application site may affect its acceptability by the public. Managed cropland and forestlands are aesthetically appealing compared to weeds and bare soil. Appropriate use and design of vegetative cover should be taken into account when planning land application systems. The choice of crop and management practice may be determined by wastewater characteristics, including volume and nutrient concentrations, length of the growing season, nature of the winter climate and the soil physical and chemical characteristics. Economic considerations will usually be of secondary importance to maximization of wastewater renovation and disposal.

The economic return from certain crops may offset part of the operating costs of a land application system. The return may be substantial in arid regions where wastewater irrigation permits the growth of crops not otherwise possible. In such areas, limited competition in local markets may add significantly to the monetary return. The economic benefits may, however, be offset by some constraints. Because land application systems have the dual objectives of wastewater treatment and crop harvest and sale, management costs will be higher and site flexibility lower than for a system where the sole objective is wastewater treatment and disposal. Machinery and labour are required to seed, cultivate, harvest and market the crop, and irrigation must be scheduled to accommodate optimum growth conditions and not necessarily to provide maximum wastewater disposal.

7 LAND APPLICATION OF TREATED MUNICIPAL WASTEWATER

7.1 Introduction

Land application of treated municipal wastewater (effluent) is the controlled application of treated wastewater onto the land surface to achieve disposal, utilization and/or treatment of the wastewater. This section provides information on wastewater characteristics and flows, water quality criteria, and descriptions of the various systems that may be used for land application. Site requirements, land area requirements, crop selection, treatment efficiencies, pretreatment and storage requirements and suggestions for monitoring of the various options are also considered.

Of primary importance in the application of treated wastewater to land is the use of water and nutrients to produce crops and provide an economic return. Other objectives may be to replace conventional irrigation water with treated wastewater in areas where irrigation is practised, or to provide additional treatment of wastewater, particularly where high rate systems are employed. The advantages and disadvantages of the various options for land application of wastewater are briefly summarized in Table 31.

7.1.1 Treated Wastewater Chemistry. The chemistry of treated wastewaters depends upon the chemistry of the raw water supply, industrial inputs, the type of treatment system, the time of year and the amount of groundwater infiltration into the collection lines. However, most effluent compositions fall within the ranges presented in Table 32.

In a lagoon system wastewater pH is generally a function of the time of year with the pH increasing with temperature and aquatic growth. The electrical conductivity (EC) is a function of raw wastewater quality, the amount of infiltration into sewer lines and the detention time in the lagoons (a result of evaporation). Total nitrogen concentration is mainly related to method of treatment and time of year. Concentrations in treated wastewater are usually highest in the spring and decrease to a minimum value in August. This lower value usually corresponds with high pH of the wastewater and is likely due, in part, to the increased volatilization of ammonia with increasing pH. Total phosphorus values also decrease in the summer and this is thought to be related to the precipitation of calcium phosphate at the high pH values. These decreases in N and P appear to be related to increased algae and aquatic weed growth in the lagoon. As algae in particular are high in N and P, likely some of these nutrients are immobilized by plant growth.

TABLE 31 COMPARISON OF FEATURES AND PERFORMANCE FOR WASTEWATER UTILIZATION, TREATMENT AND DISPOSAL SYSTEMS

	Standard Rate Irrigation	High Rate Irrigation	Overland Flow	Rapid Infiltration	Wetlands Systems	Evaporation
System Requirement						
Soil permeability	moderate (medium textured soil)	moderate to high (medium to coarse texture soil)	low (fine texture)	rapid (loamy sands and gravels)	low	low
Utilization of water & nutrients	high	medium	medium to low	none	minimal	none
Slope	up to 30% for sprinkler and 6% for surface methods	same as for standard rate	1-12%	not critical	level	level
Storage	high (7-9 months)	medium (5-7 months)	medium (5-7 months)	nil	nil	very high
Land area	high	medium	medium	low	medium	very high
Water quality - salinity, etc.	very high	high	medium to low	medium to low	low	low
Pretreatment	secondary	secondary	primary	primary or secondary	primary	primary
Treatment Efficiency	very high	high	high	medium	medium	excellent

TABLE 32 TREATED WASTEWATER QUALITY FROM THREE TREATMENT SYSTEMS (data from various sources)

Parameter	Lagoon	Mechanical	
		Primary	Secondary*
pH	6.5 - 9.5		
Electrical Conductivity (dS/m)	0.6 - 3.5	0.5 - 1.5	0.5 - 1.5
BOD_5 (mg/L)	15 - 100	40 - 80	5 - 15
Suspended Solids (mg/L)	15 - 100	40 - 80	10 - 30
Total P (mg/L)	1.4 - 9.0	2 - 4	1 - 3
Ammonia-N (mg/L)	1 - 15	10 - 15	2 - 10
Nitrite/Nitrate-N (mg/L)	0 - 1	1 - 3	2 - 15
Total Kjeldahl-N (mg/L)	3 - 25	15 - 25	5 - 20
Fecal coliforms (MPN/100 mL)	$10^2 - 10^5$		

* Conventional activated sludge plants
BOD_5 - five-day biochemical oxygen demand
MPN - Most probable number

Continuous discharge mechanical plants do not exhibit the wide monthly variations in treated wastewater chemistry quality of lagoon systems. As a result, the salinity of the wastewater from mechanical plants is usually lower than that of lagoons and nutrient content is usually higher (Table 32). If storage facilities are used in conjunction with continuous discharge mechanical plants, effluent characteristics approach those of a lagoon system.

Surveys of Canadian wastewater treatment plant effluents (Environment Canada, 1983) have indicated the presence of a number of toxic organic compounds at low concentrations (Table 33). The concentrations of most of the compounds were between one and 10 µg/L. Compounds detected most frequently were the volatile organics such as chloroform and benzene, polynuclear aromatics, chlorophenols and phthalates. The impact of these low levels of toxic organics on effluent irrigation is not known.

7.1.2 **Wastewater Flows and Storage.** Wastewater treatment plants are upgraded as municipalities experience increased sewage flows. When a lagoon system is enlarged, the actual detention time initially far exceeds the required detention time and irrigation may not be required for wastewater disposal for two or three years after upgrading. In areas where evaporation exceeds precipitation, wastewater in a large storage cell could become

TABLE 33 OCCURRENCE OF TOXIC ORGANICS IN 23 TREATED WASTEWATERS

Compound	Percent occurrence at stated concentrations		
	>1 µg/L	>10 µg/L	>100 µg/L
Chloroform	92	13	
Phenol	71	25	
Benzene	46	17	4
Di-N-Butyl Phthalate	33	8	4
Anthracene	25	4	4
1, 3-Dichloropropane	17	13	4
1, 4-Dimethylphenol	13		
Pentachlorophenol	13		
Pyrene	8		
Bis (2-chloroethyl) ether	4		
2, 4, 6-Trichlorophenol	4		
Acenaphythylene	4		
Hexachlorobenzene	4		
Benzo-A-Pyrene	4		
Bis (2-chloroethoxy) methane	4		

Blank spaces in table are zeros.

too saline for irrigation because of excessive evaporative losses. Prolonged hydraulic detention can also result in the loss of plant nutrients. It is therefore often advantageous to irrigate from the treatment cell if wastewater quality is acceptable. Another alternative is to divide the storage cell into two or more compartments and use only as many compartments as necessary for storage and irrigation. This can reduce evaporation in the early stages of use.

As flows increase, the excess storage capacity decreases and the wastewater from the storage cells can be used for irrigation. Eventually, flows will increase to the point where high precipitation over a year could result in a storage deficiency. When this situation is anticipated, the lagoon system should be upgraded.

Municipalities generating predictable volumes of sewage can construct lagoon systems incorporating wastewater irrigation with considerable accuracy. The planning requires a recognition of seasonal crop moisture requirements as generalized in Figure 18.

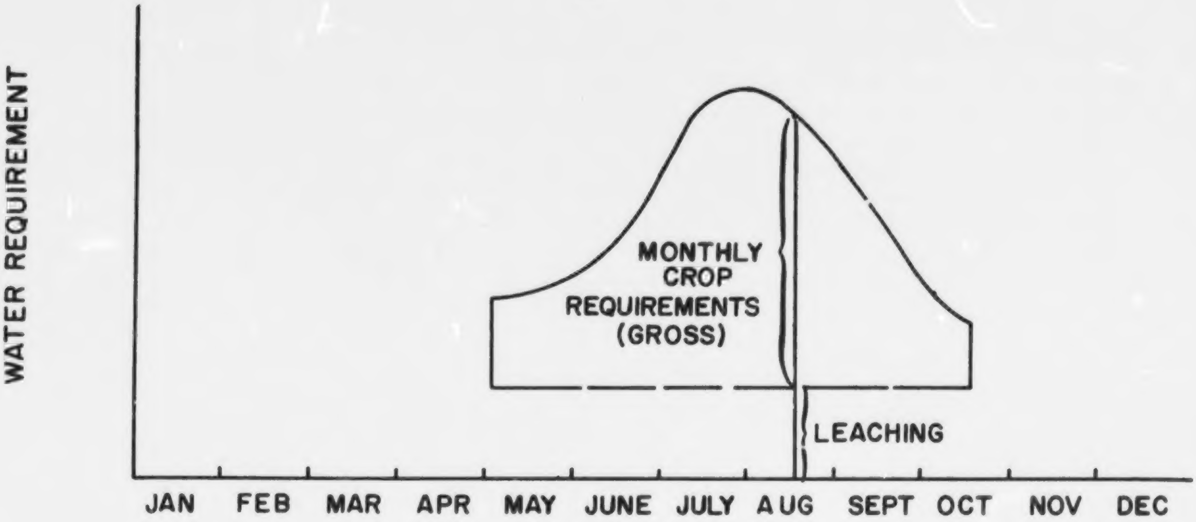

FIGURE 18 TYPICAL CROP WATER REQUIREMENTS AND APPLICATION

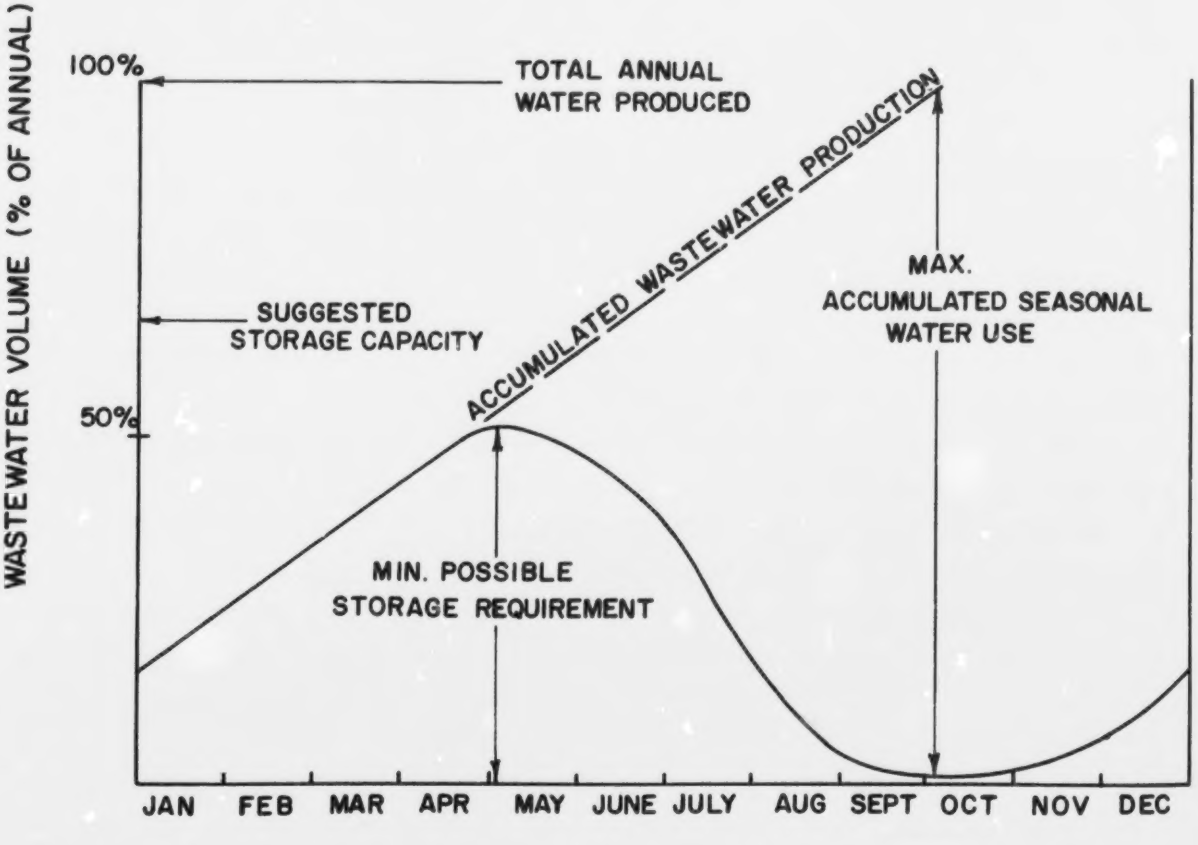

FIGURE 19 TYPICAL SEASONAL TREATED WASTEWATER STORAGE AND USE

The concept is then incorporated into the storage plan (Figure 19). Figures 18 and 19 are generalizations and will vary with climate, crop and legislation. If leaching is provided in the early spring or late fall the shape of the curve in Figure 18 will change at its extremities.

7.1.3 Irrigation Water Quality. A dynamic equilibrium exists between soil and irrigation water such that poor quality irrigation water will cause undesirable changes in soil properties. This topic is discussed in detail in Appendix B, and criteria for wastewater quality are recommended for various irrigation options.

Water quality aspects that require consideration are as follows:

(a) Salinity - A salinity problem occurs if salt in the applied irrigation water accumulates in the root zone and crop yields are reduced.

(b) Permeability - The permeability of soil can be drastically reduced as a result of a high sodium adsorption ratio (SAR) in the water.

(c) Toxicity - A toxicity problem is different from a salinity and permeability problem in that toxicity occurs within the plant. This is usually related to one or more specific ions such as boron, nickel, etc.

(d) Nutrients - Wastewater contains significant amounts of plant nutrients and the major objective of wastewater irrigation is to utilize these nutrients. The concentration of nutrients varies according to the degree and kind of treatment and the time of year that the wastewater is removed from the lagoon or storage cell. The value of the nutrients applied in wastewater irrigation depends on the cost of commercial fertilizers. To calculate the weight of a particular nutrient applied, the following equation can be used.

$$\text{kg/ha} = \frac{\text{conc. in mg/L}}{10} \times \text{cm applied}$$

The value of N, P and K per kg (1982) is as follows:

N as 46-0-0 = 70¢	P as 0-45-0 = 92¢
K as 0-0-60 = 31¢	P as 11-55-0 = 68¢

Therefore, the value of nitrogen added when 30 cm of wastewater containing a total nitrogen concentration of 10 mg/L is applied to one hectare of land is: 10/10 x 30 = 30 x \$0.70 = \$21.

The application of large amounts of effluent containing high concentrations of N can lead to toxic levels of NO_3 in crops, or to leaching of NO_3-N into the groundwater system. This situation will be rare for standard rate irrigation systems, and can be avoided by imposing loading limits. It cannot be avoided in high rate irrigation or rapid infiltration systems and, therefore, must be addressed as an adverse impact on groundwater quality. The nutrient requirements for various crops can be obtained from local agricultural offices. Phosphorus in treated wastewater is rarely of concern, as the levels are generally less than that required to meet crop demand. Phosphorus is effectively retained in the soil, eliminating the possibility of groundwater contamination.

(e) Metals - Concern has been voiced that wastewater used for land application may contain trace metals which could be toxic to soil organisms, plants and consumers of plant material. Concentrations of trace metals exceeding recommended limits are rarely observed (Appendix B).

(f) Bacteria - The bacterial quality of treated wastewater for irrigation is controversial. The major restrictions depend upon the kinds of crops grown and the elapsed time between irrigation and harvest.

Recommended wastewater quality criteria are provided for the utilization wastewater application options described in the following sections.

7.2 Wastewater Utilization Options

The primary objective of the land application options described in this section is to optimize the use of water and nutrients for crop production.

7.2.1 Standard Rate Irrigation. Standard rate wastewater irrigation can be defined as the controlled application of effluent onto land by sprinkling or surface spreading to satisfy the optimum water demand of the crop and the leaching water requirement. The objectives may be to:

(a) utilize wastewater constituents and realize some financial return through produce sale,
(b) comply with a zero discharge requirement, or
(c) provide an alternative to tertiary treatment.

The schematic in Figure 20 shows the typical hydraulic pathways for standard rate irrigation.

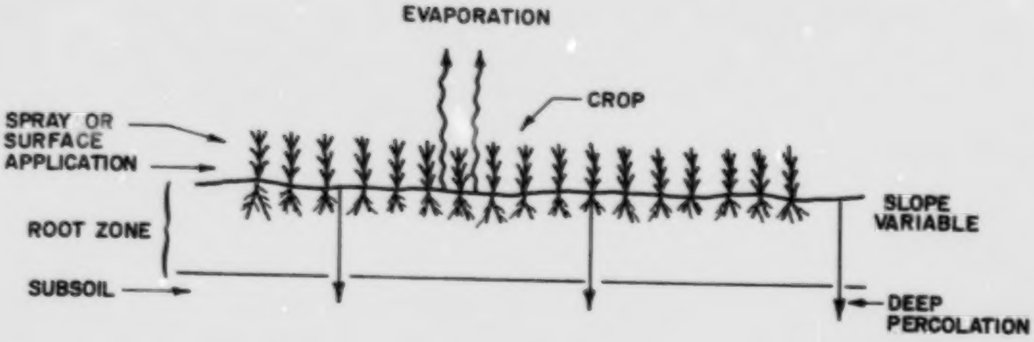

FIGURE 20 TYPICAL HYDRAULIC PATHWAYS FOR STANDARD RATE IRRIGATION SYSTEM

Because crop production is of significant importance in standard rate irrigation, the water quality standards are high relative to those for other options. Suggested criteria are presented in Table 34.

A medium textured root-zone, with a well drained subsoil is ideal for standard rate wastewater irrigation; however, different combinations of soils can be utilized provided that minor changes in operational procedures are followed. Soil survey maps and reports for the settled areas of Canada are available from Departments of Agriculture, but should be supplemented by drilling to a depth of 5 to 6 m. Most provinces have published land classification standards for irrigation which should be obtained and utilized. Crop production is not always the primary objective in land application systems, but it is necessary to establish and maintain a reasonable plant cover for the system to be effective.

Water in excess of evapotranspiration must be removed from the root-zone to prevent eventual salinization of the soil-plant system. It is obviously desirable that the required drainage occur naturally; however, if the existing or anticipated water table is near the surface, artificial drainage must be installed. The drainage water must be conveyed to an approved discharge point. Prior to site selection, a survey of the existing wells in the area should be made and the groundwater flow direction determined.

On land that has steep slopes, the applied water will run off quickly decreasing the amount entering the soil. When irrigating with treated wastewater, efforts should be made to minimize runoff. It is often required that all runoff be collected and returned to the top of the field. Sprinkler systems are usually used for irrigation with wastewater to

TABLE 34 RECOMMENDED WATER QUALITY CRITERIA FOR STANDARD RATE IRRIGATION

	Degree of Problem		
Irrigation Problem	No Problem	Increasing Problem	Severe Problem
Salinity EC (dS/m)* (affects crop water availability)	<1.3	1.3 - 3.0	>3.0
Permeability SAR** (affects infiltration rate into soil)	<6	6 - 9	>9
Boron (mg/L) (affects sensitive crops)	<0.75	0.75 - 2.0	>2.0
pH (affects sensitive crops)	Normal Range 5.5 - 9.0		

* Assume a well drained soil and a leaching fraction of 0.15.

** Assume fine and medium textured soils; can be relaxed if soils are coarse textured (loamy sands and sands).

reduce the runoff potential. Sprinklers can be used on slopes up to 10% without runoff. On slopes greater than 10%, specially designed sprinkler systems with low application rates can be used. Sprinkler systems with application rates of 0.5 to 1 cm/h should be used on fine textured soils and 1 to 1.7 cm/h on medium to coarse textured soils.

Methods used in large scale fresh water irrigation schemes such as wild flooding, contour ditch and border ditch are discouraged in wastewater irrigation due to the large volume of runoff that occurs. The border dyke flood system may have some application in wastewater irrigation. This system is described in Section 7.2.3.

Storage requirements are a function of wastewater flow, climate and crop type. Provincial regulatory requirements may dictate the required storage time. Because most wastewater irrigation schemes are associated with lagoon systems, the treatment system also serves as the storage facility. However, irrigation schemes do exist where the majority of the treatment is provided through a mechanical plant and the effluent is stored in a pond.

Standard rate irrigation implies maximum crop utilization of nutrients and water (including the leaching requirement). The land requirement depends upon the annual flow (corrected for net evaporation), annual mean moisture deficit for the area, an efficiency factor, a buffer zone requirement, moisture stored in the soil in the spring and the leaching requirement. The last two factors are opposite in sign and in most areas are approximately equal in magnitude, and therefore are omitted from calculations of land requirements. The actual annual moisture deficit for grass in Canada is shown on the map included in Section 6 (Figure 15).

The gross amount of wastewater to be applied to grass is calculated by the following equation:

$$D = M/0.80$$

where D is the annual gross requirement in mm, M is the moisture deficit in mm (Figure 15) and 0.80 is the efficiency factor which accounts for evaporative losses.

D values for other crops can be determined by multiplying D for grass by the following conversion factors:

Alfalfa and clover	1.2
Soft wheat	0.80
Hard wheat	0.75
Oats and Barley	0.65
Grass	1.0

The land area required for a given volume of wastewater is:

$$A = V/10D$$

where A is area in ha, V is the annual volume of wastewater for irrigation in m^3 and D is the annual gross irrigation requirement in mm derived from the previous equation. In most cases forage crops are preferred with standard rate effluent irrigation systems due to their high consumption of water and their long growing period.

These calculations can of course be overruled if the total nitrogen applied per year exceeds the crop requirement, which is unlikely in the case of treated municipal wastewater.

If salt build-up occurs, an occasional fall irrigation with good-quality water may be necessary to leach excess salts. Additional land may have to be purchased to allow a minimum buffer strip of 70 m between the irrigated field and any sensitive areas such as residences, schools, domestic wells, etc.

Of significant importance in site selection is the compatibility of the intended use with regional land-use plans. The regional planners or the planning commission should be consulted as to the proposed future use of the site. During a visit to the site, the current use, adjacent land use, and proximity to areas developed for residential, commercial, or recreational activities can be ascertained. On the basis of a review of master plans or discussions with local planners, the proposed future use, zoning, and proposed development of the adjacent area can be determined.

The cover crop should be selected to maximize:

a) water removal;
b) nutrient removal;
c) economic return.

Land irrigation systems have been used with:

a) forage crops;
b) grain crops;
c) turf crops;
d) forest lands, and
e) oil seed crops.

Forage crops are preferred because their relatively high water and nutrient utilization minimize land requirements. Perennial crops allow irrigation to be initiated early in the spring and continued late into the fall, reducing winter storage requirements. Excellent erosion control is also provided. Small grains and oil seed crops provide immediate income but their relatively low water and nutrient requirements make large areas of land necessary for irrigation and storage. Turf crops such as golf course fairways require high levels of nutrients and water. Irrigation of golf courses with treated, chlorinated effluent is gaining in popularity in North America. Commercial sod crops also benefit from wastewater irrigation. Forests have the potential for accepting relatively large volumes of wastewater. The upper mineral soil is protected by vegetation and surface litter against the impact of water drops. However, the use of automated sprinklers is impractical making expensive solid set systems or labour intensive manual systems necessary. Generally tree growth is increased, but financial returns may not accrue for many years. A detailed discussion of crop considerations is found in Section 6.

The degree of treatment required prior to irrigation varies with the crop grown and the anticipated use of the crop. Secondary treatment, with minor variations, is generally required by most jurisdictions.

The only discharge to the groundwater from standard rate irrigation is that provided by the leaching requirement (5-10% of the water applied) and the leachate resulting from occasional high rainfall events. The leachate quality is therefore very high

TABLE 35 TREATMENT EFFICIENCY OF STANDARD RATE IRRIGATION (ROOT ZONE)

Parameter	% Removal
BOD	98+%
SS	98+%
N	85+%
P	95+%
Metals	95+%
Microorganisms	95+%

(Table 35). Coincident with the exceptional removal of organics, solids and nutrients, the salinity of the leachate can be expected to be several times the concentration of the applied wastewater. The increase in salinity is usually predominantly due to an increase in hardness and chloride (Graveland, 1982).

A comprehensive monitoring program may be required to ensure that proper wastewater utilization is being achieved and that environmental degradation is not occurring. Groundwater, treated wastewater, vegetation and soils may have to be monitored. Generally, nitrate nitrogen is the parameter monitored in groundwater. To assess the overall impact of the system, changes in groundwater quality can be compared with the quality of background wells. An example of a compliance and operational monitoring schedule is provided in Table 36.

In addition to changes in groundwater quality, changes in groundwater level should be monitored. The effect of elevated levels should be assessed with respect to changes in the hydrogeological conditions of the area. Changes in groundwater movement and the appearance of seeps and perched water tables should be noted; system modifications, such as underdraining or reduced application rates in the area, may be necessary.

In almost all cases, application of wastewater to land will cause some changes in soil characteristics. Important characteristics include salinity levels as measured by EC, SAR, pH, NO_3-N and P. Metal analysis may be advisable if the treated wastewater is high in metals.

7.2.2 High Rate Irrigation. High rate irrigation is intermediately placed between standard rate irrigation and rapid infiltration and, therefore, covers a wide spectrum with respect to total annual wastewater application. Generally, most of the disposal and

TABLE 36 EXAMPLE OF OPERATIONAL AND COMPLIANCE MONITORING SCHEDULE FOR A TREATED WASTEWATER IRRIGATION SYSTEM

		Sampling Frequency at Various Points			
Parameter[a]	Applied Effluent	On-site Wells (3 pts.)	Background Well (1 pt.)	Perimeter Wells (5 pts.)	Adjacent Lake (1 pt.)
BOD_5	D	-	-	-	Q
COD[b]	M[c]	Q	Q	Q	Q
Coliform, fecal	M	Q	Q	Q	Q
Flow	C[d]	-	-	-	-
Nitrogen[e]	M[c]	Q	Q	Q	Q
pH	2D[d]	Q[d]	Q[d]	Q[d]	Q[d]
Phosphorus	M[c]	Q	Q	Q	Q
Suspended solids	D	-	-	-	-
Static water level	-	M[d]	M[d]	M[d]	-
Electrical conductivity	Q	Q	Q	Q	Q

NOTES:
D = One sample or measurement per day
Q = One sample or measurement every three months
M = One sample or measurement per month
2D = Two samples or measurements per day
C = Continuous measurement and recording

[a] If filtered samples of raw wastewater indicate the concentration of a particular health-significant parameter (not given above) to be in excess of the permissible limit for drinking water sources, that parameter will be included in this schedule.

[b] Chemical Oxygen Demand. May also use TOC (total organic carbon) to establish a long-term correlation with BOD_5.

[c] Denotes 24-hour composite samples. All others are grab samples.

[d] Field measurement.

[e] Total nitrogen for effluent; nitrate-nitrogen for groundwater.

treatment occurs by deep percolation through the soil and sub-strata to the groundwater. The effect of crop evapotranspiration is secondary. This method provides treatment superior to that achieved by infiltration basins and provides some revenue in the form of a harvested crop. Land requirements are lower than for standard rate irrigation and distribution is generally less expensive.

The primary objective of high rate irrigation is to maximize percolation. Crop production is a secondary objective. This method is worthy of investigation when: permeability is limiting for rapid infiltration methods, groundwater recharge is desirable, or land purchase is limited by cost or scarcity. The soil infiltration rate is the prime design criterion for high rate irrigation, but groundwater mounding, groundwater quality and crop survival can also act as constraints.

The high leaching fraction with high rate irrigation allows the quality of irrigation water to be somewhat relaxed compared to standard rate irrigation water quality criteria (Table 37). Details are found in Appendix B.

TABLE 37 RECOMMENDED WATER QUALITY CRITERIA FOR HIGH RATE IRRIGATION

Irrigation Problem	Degree of Problem*	
	No Problem	Increasing Problem
Salinity (dS/m) (affects crop water availability)	<4	4+
Permeability (SAR) (affects infiltration rate into soil)	<6	6+
Boron (mg/L) (affects sensitive crops)	<1.0	1+
pH (affects sensitive crops)	Normal Range 5.5 - 9.0	

* Assume a very well drained soil and a leaching fraction of 1.0.

Soils for high rate irrigation schemes must be well drained, non-saline and non-sodic, and contain some clay-sized particles and preferably free $CaCO_3$ to ensure sustained P removal. The major requirement, however, is that infiltration rates can be maintained at 0.5 cm/h for up to 10 hours.

Investigations must be performed to ensure that groundwater mounding will not occur at the prescribed application rate for the entire proposed irrigated area. If natural drainage is insufficient to prevent mounding, tile drainage may be required. Topographic constraints are similar to those for standard rate irrigation.

Storage requirements for high rate irrigation can be less than for standard rate irrigation as evapotranspiration rates do not dictate the timing or the amount of irrigation. The frost-free period for a particular area would be a good design criterion for storage. As the frost-free period for the settled areas of Canada varies from 80 to 220 days, the required storage capacities also vary considerably.

The amount of land required for high rate irrigation depends upon the volume of effluent discharged and the annual rate of effluent application. Applications of 50 to 100 mm per week fall into the high rate irrigation category. Therefore, annual application, based on frost-free periods in Canada, would range from 600 to 3000 mm. Consequently, the area required for high rate irrigation would be 1/2 to 1/10 as large as the area required for standard rate irrigation where the net annual moisture deficit is 300 mm. The areal requirements can be determined by the use of the equation:

$$A = V/10D$$

where A is the area in ha, V is the volume of wastewater for irrigation in m^3 and D is the annual application in mm. Double ring infiltration tests are probably the best method of determining D. Site-specific testing is required to ensure that soils can accept the suggested application rate. It is recommended that, for municipalities where there is population growth, the system be designed for a future wastewater flow. This allows for adjustments in area and design parameters while the system is underloaded. The buffer zone recommended by the regulating authority must be included in the area requirements.

As the major objective of high rate irrigation is to treat wastewater, it is not advisable to grow annual crops. Perennial crops that are not sensitive to wet conditions would be preferable for this type of treatment scheme. Heindricks (1970) rated birdsfoot trefoil and white clover as the legumes most resistant to flooding. Timothy, reed canary grass and tall wheat grass were the grasses most resistant to flooding (Bolton and McKenzie, 1974).

The degree of wastewater pretreatment required for high rate irrigation is similar to that for standard rate irrigation, i.e., secondary treatment.

High rate irrigation systems can provide effluent treatment that approaches that of conventional irrigation for all parameters except NO_3-N. Due to the high application rates, the NO_3-N will be leached to the groundwater system. Some nitrogen will be volatilized, denitrified, immobilized by microorganisms and used by crops.

Information on treatment efficiencies were derived from U.S. publications on slow rate irrigation. A number of systems described as slow rate in the U.S. would be considered as high rate in this manual. Information from Dickenson, North Dakota (U.S. EPA, 1979) indicates that the mean annual application was 150 cm, which would exceed the moisture deficit in Canada. Wastewater quality and quality of groundwater associated with wastewater irrigation, as well as that of groundwater not associated with irrigation are given in Table 38. Wastewater irrigation resulted in an increase in salinity, COD and NO_3-N in the groundwater.

TABLE 38 HIGH RATE IRRIGATION TREATMENT RESULTS (U.S. EPA, 1979)

Parameter	Applied Wastewater	Groundwater	
		Control*	Test**
pH	8.7	8.0	7.4
BOD_5 (mg/L)	42	1.0	1.0
COD (mg/L)	248	19	59
Conductivity (dS/m)	1.69	1.96	4.14
Chloride (mg/L)	83	22	85
Ammonia-N (mg/L)	6.9	0.3	0.4
Soluble organic N (mg/L)	3.7	0.7	1.2
Nitrate - N (mg/L)	1.5	0.4	1.8
Soluble P (mg/L)	3.8	0.07	0.06
Fecal coliforms	TNTC***	0	0

* groundwater in area not irrigated with wastewater
** groundwater in area irrigated with wastewater
*** too numerous to count

The monitoring requirement for high rate irrigation should be similar to that of the standard rate system (Table 36) but could be modified according to the end use of the recovered water. If it is to be discharged, the analysis must include the parameters required by federal or provincial regulations. Public health agencies may require additional analyses if the upgraded groundwater is to be collected and reused directly.

7.2.3 Application Methods. There are many methods for applying wastewater to land; the choice depends upon many factors, such as land features, energy requirements and manpower availability. The most popular methods are described briefly in the following sub-sections.

7.2.3.1 Sprinkler irrigation. In the sprinkler irrigation method, the treated wastewater is applied in a manner similar to rainfall. The main components of a sprinkler system are the pump and motor, the supply main, the lateral line, the risers and the sprinkler heads. The system can be manual, automated, portable or stationary. Figure 21 is a simplified diagram of these systems.

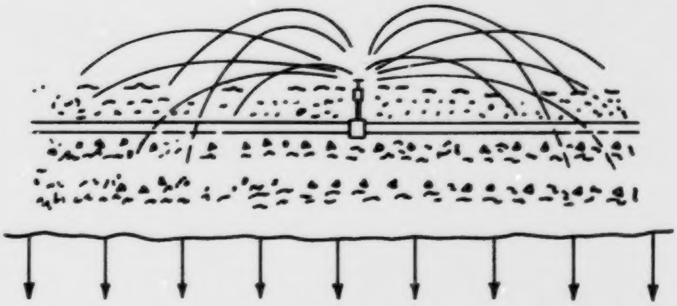

FIGURE 21 SPRINKLER IRRIGATION SYSTEM SCHEMATIC

The advantages and disadvantages of sprinkler distribution systems relative to surface distribution systems are summarized in Table 39.

Some of the more popular sprinkler system types are briefly described below:

(1) Wheel Roll System - This system consists of a lateral line which also serves as an axle for the wheels which are spaced the same distance apart as the sprinkler risers (approximately 12 m). After an irrigation set is completed, the pressure is removed and the lateral automatically drains. The lateral is disconnected from the mainline and is then mechanically moved to the next set. The mover is located in the middle of the lateral and uses a gasoline motor and an oil hydraulic pump to transmit a torque to the lateral in order to roll it to the next set. A normal lateral is 400 m in length, utilizes 32 sprinklers and covers 0.7 ha per set. Wheel roll systems can operate on slopes up to 10% and can be used on crops not exceeding 1 m in height. Rectangular fields are preferred.

(2) Centre Pivot Systems - These systems consist of a lateral mounted on high towers and attached to a pivot point at the center of the field. This system rotates around the pivot while it is irrigating and, therefore, can be operated with little labour. The speed of travel can be adjusted to control the gross application. One centre

TABLE 39 ADVANTAGES AND DISADVANTAGES OF SPRINKLER DISTRIBUTION SYSTEMS

Advantages	Disadvantages
1. Can be used on coarse textured and variable soils.	1. Initial capital cost can be high.
2. Can be used on shallow soil profiles.	2. Energy costs are higher than for surface systems.
3. Can be used on rolling terrain.	3. Sprinkler application of high salinity water can cause leaf burn.
4. Can be used on easily eroded soils.	4. Moving systems can create deep ruts in some soils.
5. Can be used with small flows.	5. Distribution is subject to wind distortion.
6. Skilled labour not required.	6. Wind drift of sprays increases the potential for public exposure to wastewater.
7. Can be used where high water table exists.	
8. Can be used for light, frequent application.	
9. Control and measurement of applied water is easy.	
10. Interference with cultivation is minimized.	
11. High application efficiencies are usually possible.	
12. Tailwater control and reapplication is not usually required.	

pivot lateral can be used on two circles by towing it from one pivot point to another. This is accomplished by turning the wheels at each tower and towing from one end with a farm tractor. Depending on the crop, climatic conditions, and soil, the system may or may not be able to keep up with two types of crop so this should be carefully examined before deciding to use one machine on two circles. Often if the crops have different use rates and require water at different times of the year it can be profitable to use one pivot on two circles. Systems can be as short as a one-tower, 100-m long unit, or as long as 800 m with 18 to 20 towers. Centre pivot systems can operate on 15% slopes and on crops 3 m in height. Circular fields are ideal, and fields must be clear of obstructions such as powerlines. Centre pivot systems have been modified for use in wastewater irrigation by directing the nozzles downward instead of upward to reduce the aerosols emitted by the system. A greater advantage is that this modification allows for cold weather irrigation, as the spray does not contact the superstructure where it could freeze and accumulate until the structure collapses with the weight of ice. This feature is especially important for high rate systems which could operate in early spring and late fall.

(3) Handmove Systems - These systems consist of 9 to 12 m lengths of aluminum tubing with one sprinkler on each length. The lateral is moved by hand, usually length by length between irrigation sets. The use of these systems is presently restricted to small areas where labour costs are relatively insignificant. This system can be enlarged to a solid set system, where irrigation can be controlled by turning valves off and on, and different areas can be irrigated without moving pipes. These systems can be utilized on slopes approaching 30%, any shape of field and any type of crop.

(4) Volume guns - Volume guns are single large-diameter sprinkler heads which discharge from 400 to 3000 L/min. The large nozzles are particularly suited to the spreading of feedlot wastes and liquid sludges. These systems have been automated in a number of ways. Due to the large nozzle size, volume guns require high pressure to get good stream breakup. This results in high energy costs. They can operate on 20% slopes, on irregular shaped fields and on any type of crop.

Sprinkler systems, due to their flexibility with respect to topography, soil type and control of application are well suited to wastewater irrigation systems. As the rate and amount of application can be easily controlled, the volume of runoff water can be minimized. The incidence of nozzle clogging is not greater when using treated wastewater than with most surface waters. Municipalities contemplating wastewater irrigation should contact provincial agencies or irrigation equipment suppliers for assistance in design.

7.2.3.2 Surface irrigation. In surface irrigation, water is applied to the ground surface at one end of the plot and allowed to spread over the plot by gravity. The conditions favourable and unfavourable for surface irrigation are presented in Table 40. Methods of surface irrigation such as wild flood, contour ditch and border ditch are not recommended

TABLE 40 FAVOURABLE AND UNFAVOURABLE CONDITIONS FOR SURFACE IRRIGATION

Favourable	Unfavourable
1. Capital not available for more sophisticated methods.	1. Land levelling costs may be prohibitive.
2. Skilled labour is available at reasonable rates.	2. Uniform distribution not achievable on permeable soils.
3. Surface topography requires little modification to make uniform grades.	3. Runoff control and return system required.
	4. Skilled labour required.
	5. Periodic maintenance of surface required to maintain uniform grades.

for wastewater irrigation as they result in large volumes of surface runoff. Methods such as border dykes, basins, furrows and corrugations offer some potential provided tail water or runoff is controlled or collected.

The **border dyke** is a form of controlled surface irrigation which utilizes both water and manpower to a high degree of efficiency. Figure 22 is a simplified diagram of a border dyke system.

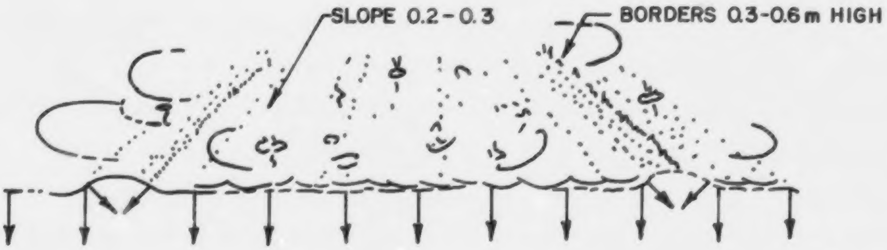

FIGURE 22 BORDER DYKE IRRIGATION SYSTEM SCHEMATIC

Land developed for border dyke irrigation is divided into strips of equal width and parallel to the direction of the downfield slope. The width of border strips is normally 5 to 15 m, the controlling factors being the amount of cross and downfield slope (the latter not to exceed 2%). Since very little land in its natural state would meet this requirement, land forming must usually be done.

The dykes separating each border are constructed with a border drag or ditch filler, in order of preference. Forming of border dykes usually takes place before seeding. The dykes are normally 12 to 18 cm high after settling. If dykes are kept fairly low, the crop may be seeded on them and no production is lost.

The length of borders varies from 90 to 800 m and is dependent mainly on surface topography, soil texture, depth of application and available water flow rate. The downfield slopes and soil texture have possibly the greatest influence on length of irrigation run. Coarser soils have higher infiltration rates and require shorter runs to prevent excessive infiltration of water. The size of the irrigation stream per border strip depends on the infiltration rate, length and width of the border strip, slope of the land and the desired depth of water application. On a fine-textured (clay) soil with a steep slope, it may be difficult to irrigate adequately without a large amount of wastewater flowing over the end of the border and into the drainage system due to the low infiltration rate.

The length of time each border strip is to be irrigated is determined by the time required to replenish the desired quantity of moisture in the soil. Usually, it takes as long as two hours on coarse soils and about five hours on finer textured soils to cover a border strip.

Construction of a low dyke (2/3 of the height of field dykes) across the lower end of the field is recommended, especially if no drainage outlet is available. This will reduce tailwater and improve water application on the end of the strip.

The border dyke method of irrigation has restrictive topography requirements; however, it is one of the most efficient surface irrigation methods available.

The **furrow irrigation** method is used specifically to irrigate row crops where furrows run down the slope. It is best suited to medium and finer textured soils because a longer length of run is possible. The furrows are formed by cultivation between the rows of the crops, with the spacing dependent on the spacing of the crop. In furrow irrigation, a stream of water is turned into and confined in the furrow; the complete land surface is not flooded as in the border dyke irrigation method (Figure 23).

The length of irrigation run varies from about 100 to 400 m depending on the slope of the land and the infiltration rate. Initially, the largest possible, non-erosive stream is turned into the furrow to insure that the water reaches the end of the furrow in 20 to 25% of the time required to irrigate the land. The size of the stream is then

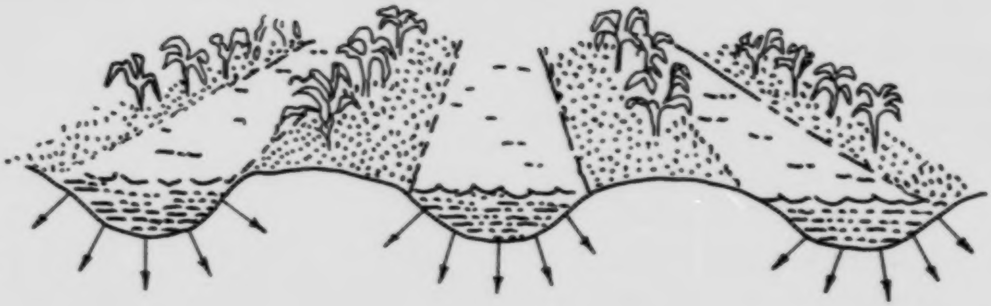

FIGURE 23 FURROW IRRIGATION SYSTEM SCHEMATIC

decreased to keep the furrow wet throughout its full length and to complete the irrigation.

This technique controls runoff and deep percolation loss at the upper end of the field and achieves uniform irrigation. It does, however, require considerable labour for adjusting the stream size. Compared to border dyke irrigation, furrow irrigation labour costs are higher and irrigation time per set is longer (at least double). Labour costs may be reduced by investing money in gated pipe to provide a better and more easily controlled water supply to the furrows. Gated pipe is simply aluminum pipe of various diameters with adjustable gates at 1 m intervals. Labour may also be reduced by automated siphon tubes equipped with water holding cups at both ends which hold water and the prime when the water level drops in the supply ditch.

Under good management (i.e., the irrigation stream is decreased with time) efficiencies as high as 70 to 75% have been achieved. However, this practice is considered impractical by many farmers; furrow irrigation efficiency is much lower in practice. Efficiency is sacrificed to save labour. Low water application efficiencies lead to salinity and alkalinity problems.

Corrugation irrigation uses small furrows to irrigate closely seeded crops. Corrugations are shaped by shovels manufactured for the purpose and are attachable to a tool-bar or cultivator shanks. Corrugations are well suited to soil that tends to crust or seal over when flooded and for fields with slight irregularities or excessive cross slopes where directional control is required. Slopes up to 6% can be effectively irrigated using corrugations. Where downfield slopes greater than 1% prevail, the irrigation water is generally confined to the corrugations. However, on downfield slopes of less than 1% and with very little cross slope, the water is allowed to overflow the corrugations and then to spread between them, with the corrugations acting only as a directional guide. For corrugation irrigation the side slopes should not exceed 20% of the downfield slope when downfield slopes are greater than 2%.

The spacing of corrugations depends largely on soil type; the coarser the soil, the closer the corrugations. Corrugation spacing varies from 46 to 110 cm. The length of run mainly depends on soil type and downfield slope because the lower end should be adequately irrigated without causing a great deal of deep percolation loss at the upper end of the field. The length of irrigation run can vary from 100 to 270 m.

The consideration of side slopes on the design of a corrugation system is not as critical as in the layout of a border dyke system since the water being applied to the land will, in most cases, be confined to the individual corrugations.

The stream size used for each corrugation is slightly smaller than for furrows. The usual method of introducing the water into the corrugations or furrows is by the use of gated pipe. Labour requirements are generally very high and irrigation efficiencies are generally less than 75%.

7.2.3.3 Cost comparisons. Total capital costs plus operating costs for sprinkler irrigation in Alberta are condensed in Table 41 using the following assumptions:

a) water is available at the edge of the field,
b) 250 mm annual gross water application,
c) 65 ha irrigated by wheel rolls,
d) 53 ha irrigated by centre pivot
e) labour costs are $8/ha, and
f) 15% interest rate.

Energy costs for electricity, natural gas, liquid propane and diesel fuel vary across Canada. Only one fuel, diesel, was used for this comparison. Other fuels or energy forms will likely be somewhat less expensive.

Cost data for surface irrigation methods are difficult to derive as land levelling costs are extremely variable. Costs for two surface irrigation methods are compared in Table 42.

The cost of land, if purchase is required, is difficult to determine due to variability of current or anticipated use and value. This cost can only be assessed on a

TABLE 41 SPRINKLER IRRIGATION COST COMPARISONS (Ring, 1983)

System	Total Capital Cost ($ per 65 ha)	Dollars per ha per year				
		Annual Fixed Cost	Labor Cost	Maintenance & Repairs	Diesel @29¢/L	Total
Wheel-roll 2 laterals	34 900	107	18	6	59	190
Wheel-roll 4 laterals	49 400	152	12	8	51	223
Centre Pivot	73 400	235	6	24	44	309
Travelling Gun Reel-irrigator	70 000	180	25	7	93	305

TABLE 42 SURFACE IRRIGATION COSTS (Ring, 1983)

System	Total Capital Cost per 65 ha	Dollars per ha per year			
		Annual Fixed Cost	Labour Cost	Maintenance & Repairs	Total
Border Dyke	40 000	93	16	7	116
Gated Pipe (gravity)	58 000	140	14	9	163

site-specific basis. Consideration should be given, however, to the fact that land purchase is an investment that is likely to appreciate.

7.3 Options For Upgrading Treated Wastewater

Section 7.2 dealt with methods to optimize the use of water and nutrients in treated wastewater for crop production. This section describes land application methods in which the primary objective is to provide additional wastewater treatment. Some crop production is possible with some of the methods.

7.3.1 **Overland Flow.** Overland flow differs from spray irrigation primarily in that a substantial portion of the applied wastewater becomes runoff which must be collected and discharged to receiving waters or stored for further treatment. A schematic view of this type of system is shown in Figure 24.

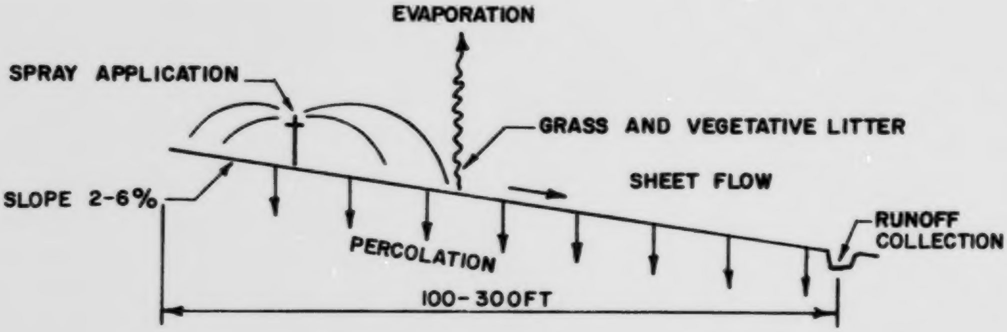

FIGURE 24 OVERLAND FLOW SYSTEM SCHEMATIC

This method of wastewater treatment is not common and little information is available with respect to water quality criteria. At this time it appears advisable to use the high rate irrigation criteria outlined in Table 37 for overland flow projects.

Overland flow is best suited for sites having surface soils that are slowly permeable or have a restrictive layer such as a clay pan at depths of 0.3 to 0.6 m. The topsoil should be of sufficient depth and quality for good cover crop establishment. It is possible to design an overland flow system on very permeable soils by constructing an artificial barrier to prevent downward water movement through the soil, although the capital costs of such construction may be prohibitive for all but the smallest systems. A minimum depth to groundwater of one metre is required to maintain aerobic conditions for plant growth. Underdrainage may be used to lower the watertable.

Winter storage requirements are similar to those for irrigation systems.

Overland flow may be used at sites with gently sloping terrain with grades in the range of 1 to 12%. Slopes can be constructed on nearly level terrain and terraced construction can be used when the natural slope exceeds about 10%. If reuse of the runoff is not possible, then a drainage system must be constructed to transport the treated wastewater from the site. It must meet federal and provincial standards for discharge into streams.

The maximum seasonal wastewater loading rate can be determined by the following equation:

$$R_W = P + D/10 + SR$$

where R_W = loading rate (cm/annum)
P = soil permeability (cm/annum)
D = water deficit (mm/annum)
SR = seasonal runoff rate (cm/annum)

Typical permeability rates used in overland flow systems range from 0.15 cm/h to 0.3 cm/h. Runoff rates typically range from 40% in the summer to 80% in the early spring and late fall. Actual runoff should be confirmed by on-site pilot studies.

The following equation can be used to calculate land requirements:

$$A_W = 0.01\ Q/R_W$$

where A_W = total land area required (ha)
Q = total annual wastewater production (m^3/annum)
R_W = seasonal water removal rate (cm/annum), as determined from the equation above.

The cover crop is an essential component of the overland flow system. It prevents soil erosion and provides nutrient uptake and a medium for the biological treatment of the wastewater. The function of the crop is similar to rock or plastic media in a conventional trickling filter.

Crops best suited to the overland flow system are grasses with a long growing season, high moisture tolerance and extensive root formation. Reed canary grass has a very high nutrient uptake capacity and yields a good quality hay. Other suitable grasses include ryegrass and tall fescue.

Wastewater pretreatment requirements are the same as those for standard rate irrigation.

Removal efficiencies for most contaminants in overland flow systems are determined primarily by loading rate, climate and type of cover crop. Suspended and colloidal organic materials are removed by sedimentation and filtration through surface grass and organic layers. The removal of suspended solids is, however, relatively unaffected by cold weather or changes in process loading parameters. Removal of total N and ammonia is inversely related to application rate, slope length and soil temperature. The rate of nitrification is reduced if wastewater is applied continuously. Phosphorus removal is by sorption on soil clay colloids and precipitation as insoluble complexes of calcium, iron and aluminum. Depending on soil colloidal content, phosphorus removal is limited to 40 to 60%. Trace element removal is dependent on similar mechanisms to those for phosphous removal.

Removal efficiencies of overland flow systems for pathogens such as viruses and indicator organisms are comparable to conventional secondary treatment systems without chlorination. Consequently, chlorination of runoff water may be required by regulatory agencies prior to discharge into streams.

Typical treatment efficiencies are given in Table 43.

TABLE 43 TYPICAL WASTEWATER CONSTITUENT REDUCTIONS FOR OVERLAND FLOW

Constituent	% Reduction Range*
BOD_5	25 - 95
Suspended Solids	33 - 85
Total N	50 - 82
Total P	0 - 80
Calcium	63 - 85
Zinc	75 - 84

* Reduction from concentrations in untreated wastewater.

Monitoring is necessary to maintain loadings within design limits. A routine monitoring program should be established for the following parameters:

a) wastewater application rate (m^3/d),
b) runoff flow rates (m^3/d),
c) wastewater quality, including BOD_5 and COD, suspended solids, total dissolved solids, total nitrogen, total phosphorus, pH, and SAR,
d) runoff water quality according to the analyses summarized in item (c) above.

Soil and groundwater monitoring are not normally required for overland flow systems since infiltration is minimal.

7.3.2 Rapid Infiltration. Rapid infiltration (RI) involves the application of wastewater (usually after some pretreatment) to land by means of basins. The wastewater percolates through the soil, undergoes a variety of physical, chemical and biological reactions and eventually reaches the groundwater. The loss of water via plants or evaporation is minor compared to the loss by percolation. The loading must be intermittent to allow for the restoration of aerobic conditions in the soil. Aerobic conditions are required for consistent removal of viruses, bacteria, organics and, the oxidation of ammonia to nitrate and removal of nitrogen by nitrification-denitrification processes. Aerobic conditions also increase the removal efficiency of phosphorus and heavy metals. Figure 25 is a schematic representation of this system.

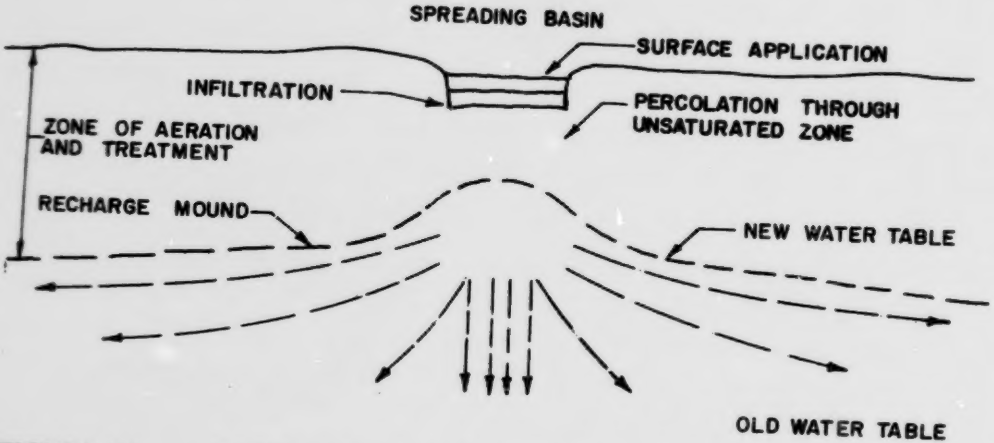

FIGURE 25 RAPID INFILTRATION SYSTEM SCHEMATIC

Very little information is available with respect to water quality criteria for rapid infiltration. As vegetation is not a vital part of treatment, it appears that wastewater salinity is not important to the treatment potential. Acceptable salinity, boron, nitrogen and phosphorus levels in the wastewater will be governed by the potential use of the groundwater downstream of the RI site. The permeability of the site is, however, very important to the performance of a RI system. Therefore, the SAR of the effluent should be below 9.

Optimum site conditions for rapid infiltration (RI) are dependent upon the quantity of wastewater to be treated and the degree of treatment required. Generally, there will be an inverse relationship between maximum wastewater application rate and the degree of treatment. Soil conditions required for a good RI site are a deep uniform sandy loam to loamy sand having the following chemical characteristics:

pH	6.0 - 8.5
Organic Matter	0.5 - 3.0%
Electrical Conductivity	2 dS/m
Sodium Adsorption Ratio	10
Cation exchange capacity	10 meq/100 g
Free Ca or Mg CO_3 should be present	

Rapid infiltration installations require permeable granular subsurface materials. A minimum of 4 m separation between the water table and the basin bottom before flooding is recommended. The areal extent, depth and permeability of the granular material are crucial parameters with respect to site selection, as the material must accept and transmit the proposed volume of wastewater away from the site to the discharge area. The water table should be greater than 1 m below the bottom of the basin during operation. Adverse natural groundwater conditions can be modified by the installation of underdrains and/or recovery wells.

Excessive slopes will restrict the usefulness of a RI site. The maximum slope is that which maintains downward infiltration with no premature lateral discharge. Generally, the maximum slope is 5% unless considerable earth moving is undertaken. Uniform flat topography will reduce construction costs.

The treatment performance of RI systems is proportional to the temperature of the applied wastewater. Detention periods in ponds and lagoons are long enough to allow the temperature of the wastewater to drop substantially during prolonged cold weather. If the temperature of the applied wastewater is too low, it may freeze before it percolates through the soil. Therefore, ponds or lagoons are not recommended for RI pretreatment methods unless cold weather storage is provided. In areas where facultative lagoons are used for treatment, the lagoons will generally be large enough to provide cold weather storage. However, the infiltration area will have to be large enough to treat the annual wastewater production during the warm weather period. Wastewater from treatment plants with short detention times will retain sufficient heat to allow continuous RI treatment and eliminate the need for storage.

Prior to site selection the planner must determine the approximate land area required for a RI system. This can be obtained by using sewage flow data and the annual amount of infiltration per unit area. The hydraulic conductivity required to estimate total infiltration can be determined from Table 44 and the following calculations. It is then suggested that a factor of 1.5 be applied to the calculated areal requirements.

TABLE 44 HYDRAULIC CONDUCTIVITIES OF VARIOUS GRANULAR DEPOSITS

Deposit	Hydraulic Conductivity (cm/s)
Clean, well sorted sand and gravel	10^{-1}
Clean sand, moderately sorted gravel	10^{-2}
Moderately sorted sand and gravel	10^{-3}
Poorly sorted sand and gravel	10^{-4}

Infiltration capacity is estimated by the following procedure:

a) Estimate site hydraulic conductivity, in cm/s.

b) Determine annual hydraulic loading and convert cm/s to m/annum (multiply by 3.15×10^4).

c) Extrapolate site area (on the y-coordinate of Figure 26) using the line most closely representing the estimated hydraulic loading rate determined.

d) Maximum daily infiltration capacity of the site in question can be read off the x-coordinate (Figure 26).

The infiltration rate must be confirmed by field testing. Areal requirements for an RI system must include:

a) infiltration basins and dykes,

b) maintenance and laboratory building(s),

c) possibly on-site treatment facilities,

d) on-site roads,

e) expansion and emergency use areas,

f) buffer strips.

The value of vegetation in RI basins is debatable. Vegetation in the basins may aid in treatment efficiency, but it tends to anchor ice and make winter operation difficult.

Most RI systems incorporate either primary or secondary treatment prior to infiltration to obtain improved treatment efficiency, minimize soil clogging, reduce public health risk and minimize odour, etc. The use of lagoons for pretreatment is usually not recommended for three reasons:

a) algae carryover in summer exacerbates soil clogging;

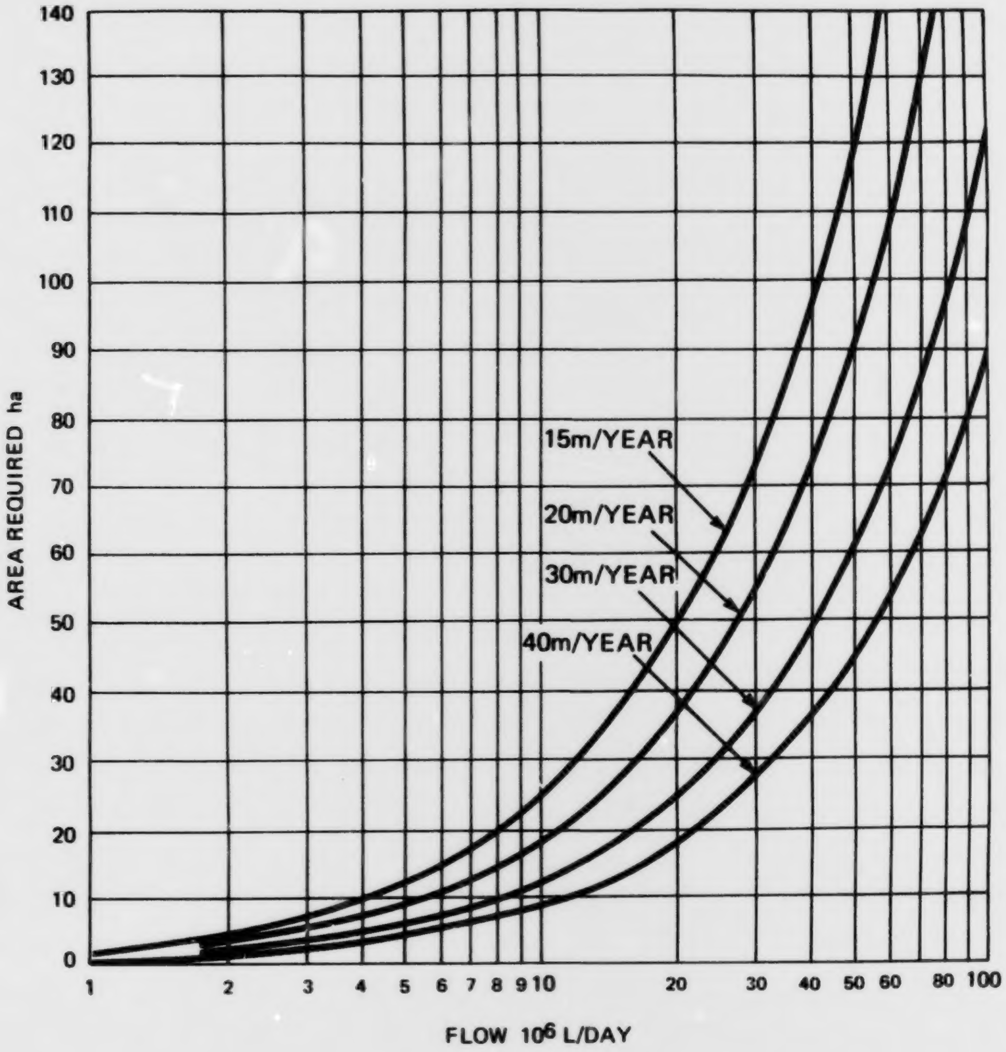

FIGURE 26 DETERMINATION OF LAND AREA REQUIRED FOR RAPID INFILTRATION SYSTEMS

b) lowering of wastewater temperature during winter retention results in increased probability of freezing the infiltration interface of the basins; and
c) land area requirements are increased.

Short-term retention ponds, such as anaerobic lagoons or primary clarifers could be incorporated into RI systems. If nitrogen removal is necessary, a maximum of primary treatment should be provided to ensure adequate carbon in the wastewater to promote the denitrification process.

Secondary pretreatment can be provided by any short detention process such as trickling filters, rotating biological contractors, activated sludge processes, etc., whereby effluent temperatures are not substantially reduced. Nitrification and denitrification processes are both temperature dependent and will not function at temperatures below 5°C.

The loading cycle of the RI basin depends upon the objective of the treatment system. The optimum nitrogen removal objective requires relatively short periods of loading and rest periods so that the basin soil is alternately aerobic and anaerobic.

Canadian RI systems would likely require an altered loading cycle with respect to seasons because longer resting periods may be required for soil drying and aeration during winter. Decreasing the application rate and increasing the length of the application and resting period are possible means of overcoming the problems of winter application.

Suggested loading cycles are shown in Table 45. The values given in this table are considered guidelines. Actual loading cycles should take into account site-specific conditions.

Once the loading rate and loading cycle have been established, the application rate can be calculated. For example, if the hydraulic loading rate is 20 m/annum and the loading cycle is one day of application alternated with seven days of drying, the application rate is as follows:

$$\begin{matrix}\text{hydraulic}\\ \text{loading}\\ \text{rate}\end{matrix} \times \frac{(\text{time on + time off})}{\text{time on}} \times \begin{matrix}\text{conversion}\\ \text{factor annual}\\ \text{to daily}\end{matrix} = \begin{matrix}\text{daily}\\ \text{application}\\ \text{rate}\end{matrix}$$

$$20 \text{ m/annum} \times \frac{(7 + 1) \text{ d}}{1 \text{ d}} \times \frac{1 \text{ year}}{365 \text{ d}} = 0.44 \text{ m/d} = 44 \text{ cm/d}$$

TABLE 45 SUGGESTED HYDRAULIC LOADING CYCLES FOR RAPID INFILTRATION SYSTEMS (ALBERTA ENVIRONMENT, 1981)

Objective of Preapplication Treatment	Preapplication Treatment Level	Season	Application Period (Days)	Drying Period (Days)
Maximize infiltration and rates of nitrification	Primary	Summer	1-2	5-7
		Winter	1-2	7-14
	Secondary	Summer	1-3	4-5
		Winter	1-3	5-12
Maximize nitrogen removal	Primary	Summer	1-2	10-14
		Winter	1-2	12-18
	Secondary*	Summer	7-9	10-15
		Winter	9-12	12-18

* Assume secondary treatment already in place.

The application rate should be used to determine the maximum depth of the applied wastewater. If the measured basin infiltation rate is 15 cm/d, the maximum wastewater depth is (44 - 15) cm/d = 29 cm.

In general, maximum wastewater depth should not exceed 46 cm with a preferable maximum depth of 30 cm. If the wastewater depth calculation indicates the recommended maximum will be exceeded, either the loading rate should be decreased or the loading cycle adjusted until the maximum basin depth is acceptable.

Soils are excellent filtering mechanisms for removal of suspended solids, BOD_5 and bacteria. Nitrogen removals are generally poor unless specific operational procedures are established to provide alternating nitrification and denitrification conditions. Adjusting application cycles, supplying an additional carbon source, using vegetated basins, reducing application rates and recycling portions of the renovated water can result in the removal of about 80% of the nitrogen, primarily through denitrification, during the summer. Winter removal rates will likely be lower as nitrification-denitrification is quite temperature dependent. Ammonia can be removed to 1 mg/L or less.

Phosphorus removals range from 70 to 99% and largely depend on soil characteristics. As soils do not have an unlimited phosphorus adsorption capacity, the treatment efficiency of a rapid infiltration site and its life span could be limited by the soil and wastewater characteristics. Removals are related also to the residence time of the wastewater in the soil and the distance of travel.

Rapid infiltration systems are designed to treat wastewater. After treatment the water can be utilized for irrigation or recreation (following recovery through wells or under drains), groundwater recharge, or surface water recharge (where proper conditions exist).

A monitoring program should provide applied wastewater quality, the quality of groundwater affected by the RI system and, if required, an analysis of the soil affected by the RI system. Several groundwater samples should be collected from sites expected to be influenced by RI and compared with samples from areas not affected by wastewater infiltration. The information derived from monitoring is useful in assessing operational methods, such as loading cycles, etc., and in forecasting the life span of the site. Some soil samples should be stored for reference.

An example of a monitoring program intended for use with a large RI system is presented in Table 46. Sampling frequencies indicated are for routine operations; more frequent sampling would be required during startup.

7.3.3 **Wetland Systems.** In recent years, the potential for aquaculture and wetland application for wastewater treatment has received increasing attention in North America. It has been suggested that biological treatment systems such as marshes and wetlands are capable of removing organic and inorganic wastewater constituents, degrading toxic compounds such as phenols, and attenuating pathogenic organisms.

Although plant uptake is an important consideration in contaminant, particularly nutrient, removal it is only one of many active removal mechanisms in the wetland environment. The principal removal mechanisms are summarized in Table 47. Removal mechanisms have been classified as physical, chemical and biological and are operative in the water column, the humus and soil column beneath the growing plants, and at the interface between the water and soil columns. Because most of the biological transformations take place on or near a surface to which bacteria are attached, the presence of vegetation and humus is very important. Wetland systems are designed to provide maximum production of humus material through profuse plant growth and organic matter decomposition.

Until recently, attention has largely focused on the use of natural wetlands for tertiary treatment of wastewaters. Artificial wetlands, however, offer greater scope for general use and are not restricted by many of the environmental concerns and user conflicts associated with natural wetlands. Unlike natural wetlands, whose use is limited by availability and proximity to the sewage source, engineered marshes can be built

TABLE 46 SAMPLE MONITORING PROGRAM FOR LARGE RAPID INFILTRATION SYSTEM

Parameter	Frequency of analysis*				
			Groundwater		
	Applied Wastewater	Soil	On-site well	Perimeter wells	Background wells
Flow	C	-	-	-	-
BOD_5 or TOC	M	-	Q	Q	Q
COD	M	-	Q	Q	Q
Suspended Solids	M	-	-	-	-
Total N	M	Q	M	M	M
Nitrate - N	-	-	M	M	M
Total P	M	M	M	M	M
Fecal Coliforms	M	-	Q	Q	Q
pH	M	Q	Q	Q	Q
Total dissolved solids	M	-	Q	Q	Q
Alkalinity	M	-	Q	Q	Q
SAR	M	Q	Q	Q	Q
Depth to groundwater	-	-	M	M	M
Heavy metals	P	P	P	P	P
Trace organics	P	P	P	P	P
Chloride	M	-	M	M	M

* C = continuously
M = monthly
Q = quarterly
P = periodically, or as required

for design and management options and can provide superior performance and reliability (Wile et al., 1982).

Artificial wetlands can be constructed almost anywhere but preferable locations would be in marginal areas to reduce competition for other land uses. In Ontario, experimental systems have been built in heavy clay soils at Listowel (Black et al., 1981) and in an abandoned mine tailings basin at Cobalt. A demonstration facility in Saskatchewan consisting of lagoons and ditches uses both gravel and natural soil

TABLE 47 WASTEWATER CONTAMINANT REMOVAL MECHANISMS IN WETLANDS

Mechanism	Contaminant Affected*								Description
	Settleable Solids	Colloidal Solids	BOD_5	Nitrogen	Phosphorus	Heavy Metals	Refractory Organics	Bacteria & Virus	
Physical									
Sedimentation	P	S	I	I	I	I	I	I	Gravitational settling of solids (and consituent contaminants) in ponds/ marsh settings.
Filtration	S	S							Particulates filtered mechanically as water passes through substrate, root masses, or fish.
Adsorption		S							Interparticle attractive force (van der Waals force).
Chemical									
Precipitation					P	P			Formation of or co-precipitation with insoluble compounds.
Adsorption					P	P	S		Adsorption on substrate and plant surfaces.
Decomposition							P	P	Decomposition or alteration of less stable compounds by phenomena such as ultra-violet irradiation, oxidation, and reduction.
Biological									
Bacterial Metabolism**		P	P	P			P		Removal of colloidal solids and soluble organics by suspended, benthic, and plant-supported bacteria. Bacterial nitrification/denitrification.
Plant Metabolism**							S	S	Uptake and metabolism of organics by plants. Root excretions may be toxic to organisms of enteric origin.
Plant Absorption				S	S	S	S		Under proper conditions significant quantities of these contaminants will be taken up by plants.
Natural Die-Off								P	Natural decay of organisms in an unfavourable environment.

* P = primary effect, S = secondary effect, I =incidential effect (effect occurring incidental to removal of another contaminant).
** The term metabolism includes both biosynthesis and catabolic reactions.

substrates at Humboldt (Lakshamn, 1980). Since grading and excavating represent a major cost factor, topography is an important criterion in site selection. In heavy clay soils, additions of peat moss or top soil will improve soil permeability and accelerate initial plant growth.

Land requirements depend upon hydraulic loading. For example, at a loading rate of 200 m^3/ha•d, a 4 546 m^3/d community would require 27 ha of wetland plus additional land for pretreatment facilities.

Because cattails, *Typha* spp. and bulrushes, *Scirpus* spp. are widespread in nature, hardy, capable of thriving under diverse environmental conditions, and easy to propagate, they represent an ideal plant species for artificial wetlands. They are also capable of producing a large annual biomass and root structure, providing a large plant-surface/water interface for bacterial activity. When harvesting is practised they also provide greater potential for N and P removal than most other plant species.

A geometric configuration providing large length to width ratios or uniform flow distribution by means of internal berming or barriers is essential in wetland facility design. Such flow distribution prevents short circuiting and ensures maximum contact between wastewater and plant/soil materials.

Results obtained to date at the Listowel project (Black *et al.*, 1981) suggest that hydraulic loading rates of some 200 m^3/ha•d and detention times of about seven days will provide maximum treatment efficiency. Retention time may be controlled independently of hydraulic loading by controlling liquid depth. A large liquid depth is preferable in winter to compensate for ice and snow cover.

Artifical wetlands may be designed to accept wastewater with minimal (coarse screening and communution) pretreatment. However, the level of pretreatment will influence the quality of the final effluent and therefore overall treatment objectives must be considered. Based upon studies at Listowel, some pretreatment of suspended solids and BOD_5 is desirable to prevent sludge accumulation and to reduce oxygen demand in the upper reaches of the marsh. Since there is no permanent escape mechanism for phosphorus within the wetland, phosphorus reduction by chemical addition is also recommended as a pretreatment step to ensure continued satisfactory phosphorus removal within the marsh. In Ontario, optimal pretreatment is considered to be a facultative aerated cell (5-10 day retention) with continuous alum (or ferric chloride) addition to reduce BOD_5, suspended solids and phosphorus. This is possible at minimal capital and operating costs.

The treatment efficiency of a wetland system depends upon many factors including design, hydraulic loading, detention, temperature, feed wastewater quality, etc., with ranges reported in the literature for various constituents as outlined below (Reed and Bastian, 1980):

Constituent	% Removal Efficiency
BOD_5	50-90
COD	50-90
Nitrogen	30-98
Phosphorus	20-90

Treatment efficiencies at the Listowel facility, a channelized marsh receiving aeration cell effluent, during the first year of operaton were as follows (Black et al., 1981):

Constituent	% Removal (Seasonal Range)
BOD_5	74-97
Suspended Solids	85-98
Total P	71-99
Soluble P	neg.-97
Total N	30-93
Ammonium - N	4-99

Monitoring is necessary to maintain loadings within design limits. A routine monitoring program should be established for the following parameters:

a) wastewater application rates (m^3/d);

b) discharge flow rates (m^3/d);

c) wastewater quality, including BOD_5 and COD, suspended solids, total dissolved solids, total nitrogen, total phosphorous, pH and SAR;

d) discharge water quality according to the analyses summarized in item (c).

Soil and groundwater monitoring are not normally required for wetland systems unless losses by infiltration are significant.

7.4 Wastewater Disposal Options

Situations arise in which wastewater is not suitable for reuse (e.g., saline) and a suitable receiving water body is not available. In these situations, it is necessary to consider disposal.

Evaporation was the primary method of wastewater disposal in many cities, towns and villages on the prairies before the inception of treatment systems. The primary design parameter is the storage volume required, which will also determine the depth and area of the lagoon. Design volume is determined by estimating the volume for net gain or loss due to precipitation and evaporation over a three to five year period.

A two-cell pond system is often used. The primary cell is designed to meet the BOD_5 loading criterion for the local climate. The second cell is designed to provide the difference between the total storage required and the volume of the primary cell.

The design depth and area depend largely on the function of the pond and the topography at the pond site. The maximum depth depends on whether the storage pond is constructed with dikes or embankments on level ground or by damming a natural water course or ravine. Maximum depths of dyke ponds range from 3 to 6 m.

The lagoon should be lined with compacted clay soil for seepage control. A seepage rate less than 0.15 cm/d is desirable.

Other design considerations include wind fetch and the need for riprap for embankment protection. These aspects of design are covered in standard engineering references.

7.5 Economic Analysis

An economic analysis and comparisons should be carried out for every proposed wastewater utilization system, for upgrading and disposal alternatives, and for various mechanical treatment methods. Capital cost items of primary importance are:

a) construction costs including overhead and profit;
b) field exploration, design costs and engineering services during construction;
c) administration and legal services;
d) start-up costs;
e) interest charges; and,
f) cost of land, population relocation, right-of-way and easement.

Land purchase is usually considered a cost. However, this expenditure may be considered an investment if land values escalate with time. The cost of distribution equipment is given in Tables 41 and 42.

Operation and maintenance costs are:

a) power requirements;
b) labour;

c) supplies for maintenance of the system;

d) monitoring; and

e) chemicals.

Cost benefits accrue from:

a) sale of crops;

b) sale of treated wastewater if legally permissible or collection of operation and maintenance charges; and,

c) lease of land, as an alternative to the municipality itself conducting a farming operation.

7.6 Use of Supernatant Liquor

Supernatant liquor is a product of sludge treatment and handling at large mechanical sewage treatment plants. Digested sludge is often transported to sludge lagoons, where the sludge is allowed to settle, and the nutrient-rich liquid is drawn off after settling and returned to the treatment plant for further treatment. At some plants digested sludge is allowed to settle in the digester with the supernatant pumped directly to the primary clarifier. Characteristics of the Calgary supernatant liquor are summarized in Table 48.

Although the electrical conductivity (EC) is high, about 70% of the electrolyte is NH_4 which is used by crops and will not contribute to soil salinity.

A pilot project on land treatment of supernatant liquor, sponsored by the City of Calgary, and carried out by staff of the City and Alberta Environment, was initiated in 1972. The project objective was to utilize the land system to achieve phosphous removal by adsorption on soils, and nitrogen removal by nitrification-denitrification (Alberta Environment, 1975). Supernatant liquor was surface applied bi-weekly to a levelled plot with closely spaced tile drainage for water table control. Wastewater quality and the quantity of the applied supernatant as well as runoff and tile flow were measured. Removal efficiency for N and P was 95 and 99%, respectively, for two years; however, the project was terminated after four years of application due to a considerable reduction in infiltration rate, which resulted in excess runoff from the bottom of the plot. The reason for the sealing is unknown. The plot was established on a medium to fine textured till soil; coarse textured soils do not occur in the area.

TABLE 48 CHEMICAL CHARACTERISTICS OF CALGARY SUPERNATANT LIQUOR

Parameter	Mean of 12 Samples
pH	7.0-8.5
Electrical Conductivity (dS/m)	4.1 (1.0)*
Ca+Mg (mg/L)	123 (18)
Na (mg/L)	103 (16)
Cl (mg/L)	30 (20)
HCO_3 (mg/L)	2 200 (470)
Sodium adsorption ratio	2.3 (0.3)
Total P (mg/L)	31 (5.9)
Nitrate-N (mg/L)	3.1 (2.9)
Ammonium-N (mg/L)	438 (115)
Total Kjedahl N (mg/L)	458 (96)
COD (mg/L)	834 (239)

* Values in parentheses are standard deviations

7.7 Special Irrigation Applications

This manual generally considers the use of wastewater effluents and sludges on forage and grain crops. Wastewater irrigation from municipal waste treatment plants can be and has been used successfully for other crops.

7.7.1 Forests. Treated effluent was applied to a relatively mature stand of pine and spruce for five years (Graveland, 1980). Soils and groundwater chemistry remained relatively unchanged but wood production from the effluent-irrigated plot was 35% greater than from an adjacent non-irrigated plot (see Appendix D).

The potential evapotranspiration rate and nutrient requirements for forest vegetation have not been established to the same degree as for agricultural crops. Generally, both water and nutrient requirements for forest crops are less than for agricultural crops. Design of such systems should be done in consultation with local experts.

Equipment costs are high because a solid set irrigation system is usually utilized for applying water in a forest. Sprinkler nozzle spacing is usually closer than with low growing agricultural crops as the trees act as obstacles to the sprinkler stream. It is also recommended that lower nozzle pressures be used, to reduce erosional damage to tree bark. The economics of this type of application are usually a function of the cost of mechanical treatment plants. Forest application of wastewater has been used primarily at non-permanent facilities such as construction camps or where zero discharge is required.

7.7.2 **Turf.** Municipal effluent and mixtures of effluent and the liquid removed from sludge settling basins (supernatant liquor) have been used to irrigate and fertilize commercial turf growing land in Alberta. Detailed experimental data have not been collected; however, large amounts of nitrogen were removed from the field when the turf was harvested. The production of commercial turf in conjunction with supernatant liquor irrigation has merit because turf requires large amounts of nitrogen and supernatant liquor is an excellent source.

7.7.3 **Golf Courses.** Golf courses have a high demand for water and nutrients and are often located close to municipal sewage treatment plants. This set of circumstances often makes wastewater irrigation of golf greens a viable option. Courses that cannot discharge sewage to a municipal system must provide their own sewage treatment and disposal. Irrigation may be the only practical option. In this case, optimum use of the club coincides with the optimum requirement for irrigation of the greens and fairways; however, the volumes of effluent produced at self-contained clubs do not meet the full irrigation demand of the course. Other sources of irrigation water are required to supplement the effluent.

Most regulatory agencies look favourably upon golf course irrigation with wastewater provided certain conditions are met. These conditions usually include secondary treatment, chlorination, posting the course to inform golfers that wastewater is used on the greens and fairways, and that irrigation occur only during non-golfing hours.

7.7.4 **Commercial Tree Nurseries.** Irrigation of commercial tree nurseries is being practiced in a number of locations in Canada; however, the advantages and risks associated with this practice have not been scientifically recorded at this time.

8 LAND APPLICATION OF MUNICIPAL SLUDGE

Land application systems for municipal sludge involve spreading sludge on the surface of soil or incorporating it into soil. There are two different approaches to sludge application: (1) utilization of the fertilizer and soil conditioning properties of sludge, and (2) disposal.

Sludge utilization on land is desirable because it recycles resources and is usually more economic than disposal. Sludge contains most of the nutrients required for plant growth and is a valuable fertilizer material. In addition, sludge organic matter improves the nutrient and water holding capacity and the tilth of soil. Disposal on land wastes the nutrient and soil conditioning properties of sludge and could cause groundwater pollution unless the system is properly designed and managed.

The land application systems that are pertinent to Canada include: (1) sludge utilization on agricultural and forested land, and for land reclamation and revegetation; and (2) sludge disposal by landfilling and on dedicated land.

8.1 Sludge Production

Sewage sludge is the residue resulting from wastewater treatment. Wastewater treatment removes solids, soluble organics and, to some extent, nutrients and pathogens which contribute to environmental pollution. A major percentage of these materials end up in the sludge.

In many small communities across Canada, lagoons are employed for wastewater treatment (Section 3.2). These are earthen basins in which bacteria and algae work together to degrade organic matter with the solids settling out in the pond where they are anaerobically decomposed. Although some solids accumulate, they must be removed only very infrequently, if ever.

Larger municipalities generally are served by mechanical treatment systems which may include primary treatment, secondary treatment and now, in many cases, tertiary treatment. Primary treatment consists of gravity solid-liquid separation in a primary sedimentation tank or clarifier. The settled solids, termed primary sludge, are generally stabilized in digesters prior to final disposal. Soluble organic materials in the primary clarifier overflow in the effluent and are not treated or removed to any significant degree.

In secondary treatment, the soluble organics are degraded and removed in activated sludge tanks, trickling filters, oxidation ditches or similar processes. These systems, similar to wastewater treatment lagoons, employ a stable bacterial population to break down and utilize the organic matter as food but at much increased rates, resulting in the production of a biomass called waste activated sludge. Excess waste activated sludge is usually digested with the primary sludge. Mechanical secondary treatment processes are usually, but not always preceded by primary treatment.

Tertiary treatment processes are applied to further upgrade effluent quality to meet specific receiving water needs. Tertiary treatment operations include chemical addition for phosphorus removal, nitrification-denitrification, carbon adsorption and effluent filtration. Such unit processes may result in further solids, adding to the primary or waste activated sludge production.

8.2 Sludge Characterization

Sludge characterization is a necessary first step in the design of land application systems. Important considerations include:

a) current and future sludge quantities;
b) percent total and volatile solids;
c) nitrogen, phosphorus and potassium content;
d) heavy metals (principally cadmium, copper, nickel and zinc) and organic pollutants present;
e) pathogens and parasites present.

8.2.1 Quantity. Sludge production in a particular municipality is influenced by a number of variables including type of servicing (combined or separate sewers), degree and kind of industrialization, amount of inflow/infiltration, and treatment process employed. Consequently, both the quantity and quality of sludge produced may vary considerably from municipality to municipality; however, generalizations can be made. Table 49 provides generalized sludge design data for various degrees of wastewater treatment based upon results of an Ontario survey (Schmidtke, 1981).

The weight and volume of sludge produced increases with the degree of wastewater treatment. Primary treatment produces approximately 80 g of sludge solids/person•day at a solids concentration ranging from about 2 to 9%. Primary sludge generally contains a significant percentage of grit and other inert material. Waste activated sludge comprises primarily organic bacterial solids and is wasted at a solids concentration of 0.5 to 2%. Combined primary and secondary treatment produces about 115 g of sludge solids per person/day, at a solids concentration ranging from 2 to 6%.

TABLE 49 SLUDGE PRODUCTION - SUGGESTED DESIGN DATA*

System	kg/person•d	Volume % of Influent	kg Dry Solids per $m^3 x 10^3$
Conventional Primary	0.077	0.20	120
Upgraded Primary	0.109	0.32	169
Conventional Activated Sludge	0.114	0.38	173
Upgraded** Activated Sludge	0.145	0.51	217

* After Schmidtke (1981) based on an influent flow rate of 658 L/person•d.
** Upgraded implies chemical addition for phosphorus removal.

If iron or aluminum salts are added for phosphorus removal, sludge production may be increased by about 40% for primary treatment and 25% for combined primary/secondary treatment.

Digestion is employed to stabilize the sludge, reduce its pathogen content and reduce the mass to be disposed. During digestion, microbial decomposition of sludge organic matter reduces the mass by approximately 40%.

8.2.2 Composition. The quality and physical properties of sludge vary widely, depending upon the type of sewage, degree and type of industrialization, and degree and type of treatment. Sewage sludge is generally the point of concentration of contaminants contained in the sewage, as the primary purpose of wastewater treatment is the production of a high quality effluent.

Domestic and industrial discharges to municipal sewers may contain heavy metals, nitrogenous compounds, phosphorus, a variety of complex organic compounds and pathogens. In biological treatment systems, most of these compounds are complexed, decomposed and/or sorbed by bacterial flocs. Chemicals such as iron or aluminum salts or lime used for phosphorus removal, also accumulate in the sludge. Table 50 provides digested sludge quality data for several Ontario Ministry of the Environment facilities (OMOE, 1977).

A survey of Canadian wastewater treatment plant sludges for toxic organic substances was recently completed by Environment Canada (1983). The data indicate the accumulation of numerous compounds at concentrations three to four orders of magnitude

TABLE 50 WASTEWATER SLUDGE COMPOSITION FOR SEVERAL ONTARIO MUNICIPALITIES (Ontario Ministry of Environment, 1977)

Constituent	Number of Municipalities	Concentration	
		Median	Range
Wet weight basis			
Total Solids (%)	15	3.5	2.0 - 6.0
Volatile Solids (% of TS)	15	51	35 - 65
pH	11	7.5	7.2 - 7.8
Alkalinity as $CaCO_3$ (mg/L)	11	4800	200 - 7600
Total Kjeldahl N (mg/L)	16	1950	1300 - 2900
Ammonium-N (mg/L)	16	740	270 - 1100
Dry weight basis			
P (g/kg)	15	24	14 - 57
K (g/kg)	10	0.09	0.04 - 0.16
Ca (g/kg)	11	44	26 - 67
Mg (g/kg)	13	6.8	3.1 - 11
Fe (g/kg)	15	51	14 - 110
Al (g/kg)	12	9.6	4.1 - 61
Na (g/kg)	10	0.16	0.07 - 0.42
Cl (g/kg)	11	7.1	1.67 - 190
Cd (mg/kg)	17	10	5.0 - 260
Zn (mg/kg)	17	1600	400 - 5130
Cu (mg/kg)	17	970	280 - 2570
Ni (mg/kg)	17	120	23 - 410
Pb (mg/kg)	17	375	200 - 1280
Cr (mg/kg)	16	530	100 - 9740
Mn (mg/kg)	15	320	170 - 2090
Co (mg/kg)	16	9.0	1.00 - 42
Mo (mg/kg)	12	12	7.0 - 97
Hg (μg/kg)	13	2.1	0.43 - 4.7

higher than those present in the effluents. Compounds most likely to accumulate appear to be phthalates, polynuclear aromatics and chlorinated compounds as represented in Table 51. The protocol used for analysis comprises the extraction of air dried sludges; no analysis was made of volatile compounds. The impact of these compounds on land utilization has not been well defined although no adverse health effects have been noted from land application of sludges with these characteristics. Research is underway to learn more about the fate of toxic organics in sludges applied to land.

TABLE 51 OCCURRENCE OF TOXIC ORGANICS COMPOUND IN CANADIAN SLUDGES (ENVIRONMENT CANADA, 1983)

	Percent Occurrence at Concentration Stated *		
Compound	>1 mg/kg	>10 mg/kg	>100 mg/kg
Bis (2 ethyl-hexyl) phthalate	92	92	31
N-Nitrosodiphenylamine	54	15	0
Pyrene	38	15	15
Di-n-octylphthalate	31	0	0
Fluorene	23	15	15
Anthracene	23	15	15
Naphthalene	23	15	0
Benzo-a-pyrene	23	15	0
2,4 Dichlorophenol	15	0	0
Chrysene	15	15	0
Pentachlorophenol	8	0	0
Hexachlorobenzene	8	0	0

* 13 sludges surveyed

The use of sewage sludge in agriculture is based upon its nutrient content for plant fertilization and its organic matter content for soil conditioning. A typical sludge contains about 4% nitrogen, 2.5% phosphorus, and 0.5% potassium on a dry weight basis. At 1983 fertilizer prices of $0.50/kg nitrogen, $1.40/kg phosphorus and $0.31/kg postassium, one dry tonne of sludge has a value of about $56.50 in addition to its value as a soil conditioner. However, assuming that 40% of the nitrogen, 50% of the phosphorus and 100% of the potassium is available in the year of application, the immediate fertilizer value of sludge is about $27.00 per dry tonne.

Sludge application to agricultural land poses a number of potential environmental hazards, including heavy metal, toxic organic and pathogen buildup in soils and nitrate-nitrogen contamination of groundwaters. Every effort should be made to limit the discharge of heavy metals and toxic organic compounds to the municipal sewer system and sludge should be stabilized prior to land application to reduce its pathogen content. To avoid groundwater contamination, the plant available nitrogen applied in sludge should not significantly exceed the crop requirement.

Sludge may be applied to agricultural land as a liquid or partially dewatered solid material. Since any dewatering process considerably increases the cost and complexity of the sludge management system, liquid haulage is preferred unless haulage distances are large. It should be kept in mind that approximately one-third of the nitrogen in digested sludge is in the liquid fraction; thickening and dewatering will reduce the soluble nitrogen level significantly.

All sludges, unless treated further by dewatering facilities are fluid and readily pumpable. However, primary sludge contains a significant amount of grit material which is abrasive to pumps and pipes.

8.3 Sludge Processing Options

Depending on the ultimate utilization or disposal of sludge, the following processing options are available: stabilization, thickening, conditioning and/or dewatering.

8.3.1 Stabilization. Stabilization processes are used to reduce the putrescibility (i.e., odour potential), the pathogen content, and the volume of sludges. Principle processes are anaerobic and aerobic digestion and chemical stabilization with lime or chlorine. Chemical stabilization is not widely practiced and sludges so stabilized are generally landfilled rather than utilized on agricultural lands.

A major attraction of digestion processes is the acceptability of digested sludge for land utilization. Aerobic digestion is usually employed at small facilities because of low capital costs, whereas anaerobic digestion is attractive for large facilities because of low operating costs and because it results in the production of methane which can be used as an on-site energy source.

Detailed descriptions of stabilization processes are provided in the U.S. Environmental Protection Agency's "Process Design Manual for Sludge Treatment and Disposal" (U.S. EPA, 1979).

8.3.2 Thickening. Sludges contain "free" (not attached to any solids) and "bound" (floc and capillary) water. Thickening refers to the separation of some of the free water from the sludge to reduce its volume and the cost of stabilization, dewatering and/or disposal. A thickened sludge is usually pumpable by conventional means and has the characteristics of a fluid. Three commonly used methods of sludge thickening are gravity, flotation and centrifugation.

In gravity thickening, the sludge particles are concentrated by hindered zone settling. In flotation, fine air bubbles introduced into the system adhere to or get trapped in the floc particle structure, making it float on the surface. Centrifuges may be used for thickening when sludge characteristics make other methods unsuitable.

Generally, sludges are thickened to between 4% and 6% solids before application to agricultural lands.

8.3.3 Conditioning. Conditioning involves the biological, chemical and/or physical treatment of sludge to enable the removal of bound water (chemically held or in capillaries) and/or intraparticle water (within the cell membrane) during subsequent dewatering. The two basic techniques used for conditioning sludge are chemical conditioning, and heat treatment or thermal conditoning. Chemicals such as ferric chloride plus lime, or organic polymers are used to improve solids loading rates, solids capture and solids concentration in the dewatered cake. Thermal conditioning can result in odour problems, corrosion, high operating costs and a very high strength liquor requiring further treatment. However, thermal conditioning appears to be equally effective on all types of sludge and can be especially attractive if combined with heat recovery from incineration.

8.3.4 Dewatering. Dewatering involves the removal of water from sludges beyond what can be achieved by thickening. This process, therefore, removes any remaining free interparticle water together with some of the intraparticle water. Selection of the appropriate dewatering process requires consideration of the pretreatment and the ultimate disposal of sludges since different solids concentrations are achieved by different dewatering processes.

Dewatering may be accomplished by natural processes through the use of sludge drying beds, lagoons, or freeze-thaw, or by mechanical processes such as vacuum filters, belt filters, plate filters or centrifuges. However, sludge generally is not dewatered prior to land utilization because of the added cost and the large loss of soluble nitrogen.

8.3.5 Disinfection. Disinfection of wastewater sludge refers to the destruction or inactivation of pathogenic organisms to minimize health hazards associated with sludge handling and disposal, and to enhance its acceptability to the public. Although well digested sludges have substantially reduced virus and bacteria levels compared to undigested sludges, digestion is not very effective against parasitic cysts and cannot be considered a disinfection process. Digested sludge is generally suitable for land application, however, without disinfection.

Three methods are currently available to disinfect sewage sludge: addition of lime or chlorine, high energy irradiation and pasteurization. Lime treatment provides a high level of bacterial and viral disinfection, although tuberculosis bacteria and some parasitic eggs may remain viable. A sludge pH of near 12 is required; this is equivalent to about a quarter tonne of lime per tonne of sludge solids. Chlorine, applied at a dosage of about 1 000 mg/L, is a good bacterial disinfectant but may be ineffective against parasitic ova and cysts. Pasteurization at 70°C for at least 30 minutes inactivates parasitic ova and cysts and also reduces bacteria and viruses to below detection levels. Generally, direct steam injection is employed. The heat for pasteurization can be derived from methane gas produced by anaerobic digestion.

Disinfection of sewage sludge by high energy irradiation is a fairly recent application of a techology widely used in other fields such as the medical and food industries. Irradiation with γ- or β-rays to an absorbed dose of about 1 Mrad provides effective inactivation of pathogens in sewage sludge. Sludges are usually stabilized prior to disinfection by pasteurization or high energy radiation since these treatments do not reduce their volatile solids content and odour.

8.3.6 Composting. Composting is the aerobic thermophilic decomposition of organic wastes. The compost product has a slight musty odour, is moist, dark in colour and can be bagged for distribution. Essentially, sludge is converted into a product with the general appearance and many of the characteristics of a fertile muck soil. Composted sludges are low in nitrogen due to complete mineralization and loss by volatilization of organic nitrogen during the composting process. They are considered good soil conditioners but relatively poor fertilizers.

Compost technology for wastewater sludge has progressed to such an extent that it differs significantly from the less controlled processing and composting of solid wastes. Thus, past poor publicity concerning solid waste composting need not discourage the use of sludge composting as a viable treatment alternative.

Composting systems fall into three categories: static aerated pile, windrow, and mechanized or enclosed systems. The static aerated pile and windrow systems have been used almost exclusively in sewage sludge composting because of their low cost and demonstrated performance. The static aerated pile does not require turning or mixing after establishment since proper blending and provision for mechanical aeration are employed when the pile is assembled. Consequently, the static aerated pile system can be used for composting unstabilized sludge. Windrow systems, on the other hand, must be periodically turned for aeration, thereby releasing noxious odours if the sludge has not been previously stabilized.

The City of Windsor, Ontario is currently using the aerated pile method to compost approximately 90 tonnes of unstabilized dewatered sludge cake per day at the West Windsor Pollution Control Plant (Faust and Romano, 1978). Wood chips are used as the bulking agent and are about 80% recoverable for subsequent use. The temperatures reached within the pile are of sufficient magnitude and duration to achieve adequate pathogen kill at all times of the year. The cost of composting is about $11/tonne of sludge cake. The compost is being used for park development and landfill restoration and is being tested as a golf fairway dressing and as an amendment for agricultural lands.

There is little North American experience to date with the enclosed mechanical sludge composting system although several such proprietary units are on the market. A mechanical composter was installed as a component of the Ontario Ministry of the Environment's Resource Recovery Centre in Toronto. A mixture of aerobically digested sludge (3% solids) and the heavy organics fraction following refuse separation is mixed in a pug mill and composted for five days. The composting material is aerated and moved toward the centre discharge of the circular digester vessel by multiple augers. A conveyor at the bottom of the composter removes the finished product. This compost is being tested as an agricultural land amendment and for reclamation of gravel pit areas.

8.4 Utilization on Agricultural Land

Guidelines for sludge utilization on agricultural land have been adopted in Alberta (Alberta Environment, 1982) and Ontario (OMAF/OMOE, 1981) and are referenced frequently in this section.

8.4.1 Preliminary Planning. Basic information should be obtained concerning local, provincial and federal regulations, sludge quantities and characteristics, and an approximate estimate of the land area required.

A planning team should be formed of people who are interested in the proposed program and whose knowledge and support are required. A main responsibility of the planning team is to solicit and obtain public support for the program, particularly from potential sludge users and local government. The importance of obtaining public support cannot be over-emphasized. Many projects have failed because its importance was not recognized.

8.4.2 Site Selection. Site selection procedures normally begin after it has been determined that sufficient land area is available for a sludge utilization program. An estimate of the total area required is obtained by dividing total sludge quantity by an assumed application rate. All potentially available land within about 50 km of the treatment plant can be considered. Soil survey maps, local extension agents and county planners can be used to screen out potentially unsuitable areas, such as flood plains, steeply sloping land and land adjacent to urban development.

After preliminary screening, potential sites can be studied in more detail. Inspection by qualified personnel should be conducted to evaluate a number of characteristics including soil pH and texture, depth to groundwater, depth to bedrock, slope, distances to specified features such as watercourses, residences, etc., and land use. A classification of sludge application sites based on soil characteristics, topography and geology developed for Alberta is presented in Table 52.

With the exception of molybdenum and boron, the potentially toxic elements in sludge are more soluble in acid than in neutral and calcareous soils. To minimize plant uptake of toxic elements it is recommended that soils receiving sludge have a near or above neutral pH. In Ontario the soil pH must be ≥ 6.0 (OMAF/OMOE, 1981) and in Alberta ≥ 6.5 (Table 52). Proposed sites not meeting these requirements may be upgraded by liming. The minimum soil pH requirement may be waived if sludge is derived from a wastewater treatment facility with a lime-based phosphorus removal system.

The ease with which water passes through soil, i.e., the soil permeability, is related to soil texture. Medium to fine textured soils exhibit moderate permeabilities and are preferred for sludge application (Table 52). Coarse textured sands and gravel are highly permeable and sludge application may cause groundwater contamination. Very fine textured soils are only slightly permeable and are subject to runoff. Organic soils are unsuitable for sludge application because they require neither phosphorus nor organic matter for crop production and there is a risk of groundwater contamination.

TABLE 52 CLASSIFICATION OF SLUDGE APPLICATION SITES BASED ON SOIL CHARACTERISTICS, TOPOGRAPHY AND GEOLOGY (Alberta Environment, 1982)

	Suitable for sludge application			Not suitable for sludge application
	Class 1[a]	Class 2	Class 3	Class 4
pH	≥ 6.5	≥ 6.5	≥ 6.5	< 6.5[b]
Texture[c]	CL,SiCL,SiL, Si,SiC,L,SCL,	C,HC	LS,SL	Sand and gravel[d]
Slope[e] %	0-2	2-5	5-9	>9
Depth to Potable Aquifer (m)	>5	3-5	2-3	<2

[a] Recommended sludge application rates to sites decrease as follows: Class 1 > Class 2 > Class 3. Class 4 sites may not receive sludge. Sites are classified at the level of the least favourable characteristic.

[b] Class 4 sites with pH <6.5, which would otherwise be classes 1 or 2 may be upgraded by liming to pH 6.5.

[c] As determined on samples from representative soil horizons to a depth of at least 30 cm; C-clay, L-loam, Si-silt, S-sand, H-heavy, e.g., SiCL - silty clay loam.

[d] Other class 4 sites include stream valleys, intermittent drainage areas and organic soils.

[e] Restriction of sludge application rates based on slope considerations apply only when surface application methods are employed. Slope criteria can be relaxed if sludge is applied by subsurface injection.

The time required for soils to dry following rainfall and become suitable for sludge application with wheeled implements is also a function of soil texture. Fine textured soils with low permeabilities require longer drying times than medium textured soils with higher permeabilities.

Site suitability for sludge application increases with increasing soil depth because groundwater contamination is less likely to occur where soils are deep than where they are shallow. However, there is uncertainty concerning the minimum acceptable depth to groundwater. In Alberta, it is defined as 2 m for all soils (Table 52), whereas in Ontario it varies with soil permeability. A minimum depth of 0.9 m is defined for soils with slow to moderate permeability (OMAF/OMOE, 1981). Slow to moderate permeability is defined as 1.27 to 25.4 mm/h and moderately rapid to rapid as 25.4 to 127 mm/h. In Ontario a minimum acceptable depth to bedrock of 1.5 m is defined for all soils.

Site suitability for surface application of sludge decreases with increasing slope (Table 52) because runoff and surface water contamination are more likely to occur on steeply sloping land than on flat or gently sloping land. Surface application on land with >9% slope is not allowed in Alberta and Ontario (OMAF/OMOE, 1981). However, in Alberta slope criteria for site classification can be relaxed if sludge is applied by subsurface injection.

Land application of sludge should not be practiced in promixity to a number of environmentally and socially sensitive features such as waterways, water wells, residences, etc. Minimum distances from many such features have been defined for Alberta (Table 53). Municipal authorities and haulage contractors are advised that it may be in their interest to exceed these minima to ensure public acceptance of sludge spreading programs.

TABLE 53 MINIMUM ACCEPTABLE DISTANCES BETWEEN SLUDGE APPLICATION SITES AND SPECIFIED FEATURES (Alberta Environment, 1982)

Feature	Distance (m)[a]	
	Minimum	Preferred
Rivers[b], Canals[b], Creeks[b], Intermittent Drainage Courses, Lakes, Sloughs, Dugouts	30[c]	50
Water Wells	20	50
Areas Zoned Residential or Devoted to Urban Use	500[c]	800
Occupied Dwellings	60[c]	100
Road Allowances	10	20
Public Building Perimeters	10	30
Public Buildings	60[c]	100
School Yard Boundaries (School in Session)	200[c]	500
School Yard Boundaries (School not in Session)	20[c]	20
Cemeteries, Playgrounds, Parks, Campgrounds	200[c]	500

[a] Greater separation distances may be required based on local topographic and climatic conditions.

[b] Distances required are from the major break in slope.

[c] Distances can be reduced by 67% if sludge is subsurface injected.

In Ontario, it is recommended that the minimum distance between a sludge application site and a watercourse be determined by land slope and soil permeability (Table 54). It is also recommended that sludge not be applied within 90 m of a water well or individual residence or within 450 m of an area of residential development.

TABLE 54 MINIMUM DISTANCES BETWEEN SLUDGE APPLICATION SITES AND WATERCOURSES (OMAF/OMOE, 1981)

Maximum Sustained Slope	For Sewage Sludge Application May to November Inclusive	For Sewage Sludge Application December to April Inclusive
0 to 3%	60 m	180 m
3 to 6%	120 m	180 m
6 to 9%	180 m	No sewage sludge to be applied
Greater than 9%	No sewage sludge to be applied unless special conditions exist.	No sewage sludge to be applied

Note: The values shown are for soils of moderately rapid to rapid permeability (25.4 to 127 mm/h). For soils of slow to moderate permeability (1.27 to 25.4 mm/h), the distances should be doubled and spreading should be suspended during March and April when runoff is expected.

Sewage sludge is produced continuously and the disposal requirements frequently are out of step with agricultural practices. However, sludge utilization systems should be designed to complement the normal agricultural cropping patterns in the community. These patterns have evolved because of favourable soil, climatic and economic conditions, and respecting them will maintain good public relations for sludge application.

Where the cropping pattern includes fallow periods (e.g., the prairie region), land availability for sludge application is unlikely to present a problem. However, where fallowing is not practised, land will typically be available for sludge application only during certain times of the year. Some flexibility is possible depending upon the crops grown. Corn and soybeans are planted late in the spring and harvested late in the fall, making land available for short periods in both those seasons. Silage corn makes land available about one month earlier than grain corn. Cereal crops are planted in the spring or fall and are harvested in July to early September, making land available in late summer and early fall. Forage crops harvested in early summer make land available then and pasture land can receive sludge at any time. However, regulations requiring a waiting period between sludge application and grazing must be observed.

An alternate management system is needed when land is not available because of cropping or inclement weather. Several possibilities include: contracting with the agricultural community to maintain land available for sludge application, maintaining sludge storage capacity, landfilling or incineration.

8.4.3 **Pre-Application Treatment.** Sludge should be stabilized prior to application on agricultural land in Canada. Stabilization reduces pathogen and odour problems and avoids putrefaction which would attract vermin. Stabilization by anaerobic digestion reduces the sludge mass by approximately 40% through conversion of organic matter to methane, carbon dioxide and water. Although it is generally agreed that sludge should be stabilized prior to application on agricultural land, raw sludge may be surface applied to field crop land in England (Alderslade, 1980), and injected into soil in Denmark, Sweden and Finland (Commission of the European Communities, 1981). A study conducted at Winnipeg indicated that the health risk associated with injection of raw sludge was not greater than with injection of anaerobically digested sludge (Carroll and Ross, 1983). Full scale injection of raw sludge is planned at Winnipeg, with continued microbiological monitoring.

8.4.4 **Storage Requirements.** Storage facilities are required to hold sludge during periods of inclement weather, equipment breakdown, frozen ground, and when access would damage the soil structure and/or crops. Storage capacity can be provided by digesters, holding tanks, lagoons, drying beds and stock piles. Lagoons, drying beds and stock piles should be located well away from residential development to avoid odour nuisance and be diked and enclosed by fencing. Groundwater monitoring should also be provided for the surrounding area.

Four to six months of storage capacity is required for most of Canada to account for periods when soils are inaccessible due to snow or rain. Raw sludge storage is not recommended because of odour generation.

8.4.5 **Handling and Transportation.** Care should be exercised when handling and transporting sewage sludge because of the potential for odour nuisance and unsightliness. The choice of handling equipment is determined by the solids content of sludge as outlined in Table 55. The choice of transportation equipment depends on:

a) the nature, consistency and quantity of sludge,
b) the distance to the application site,
c) the projected lifetime of the site, and
d) the degree of equipment flexibility required.

TABLE 55 SLUDGE SOLIDS CONTENT AND HANDLING METHODS (White, 1976)

Sludge Type	% Solids Content	Handling Methods
Liquid (slurry)	1-13	Gravity flow, pump, transport in tank
Semi-solid ("wet" solids)	8-30	Conveyor, auger, transport in watertight box
Solid ("dry" solids)	25-80	Loader, conveyor, transport in box

Sludge transportation methods are summarized in Table 56. The most common method for liquid sludge transport is by tank truck. Flexibility and simplicity of operation are the key reasons for its popularity. The sludge can be land applied directly from the truck.

8.4.6 Application Methods. Sludge may be applied to agricultural land in liquid or solid form (Table 57). Systems for liquid sludge may employ surface or subsurface application whereas systems for solid sludge employ surface application. Liquid sludge application offers the advantage of relative simplicity. Dewatering is not required and inexpensive liquid transfer equipment can be used. Subsurface application of liquid sludge offers several advantages over surface application. It minimizes nitrogen loss through runoff and ammonia volatilization, and avoids odour, vermin and public acceptance problems.

Sludge application with inappropriate equipment and when conditions are unsuitable can cause serious compaction and structural damage to soils. Precautions must be taken to avoid soil damage because it results in reduced crop yields and increased cultivation costs. One such precaution is to use application equipment with flotation tires.

8.4.7 Crop Selection. Cereals, corn, oil seeds and forage are the major crops grown in Canada and sludge is an effective source of nitrogen and phosphorus for their

TABLE 56 SLUDGE TRANSPORT METHODS (White, 1976)

Sludge State and Transport Equipment	Characteristics	Comments
Liquid		
Fixed pipeline	Installation below frostline necessary for year round operation.	High capital cost. Minimum sludge velocity of 30 cm/s required to maintain solids in suspension.
Tank truck	Capacity-2.5 m^3 to maximum allowed on road.	High speed. Principal use is road transport. Can be used for field application.
Farm tractor and tank wagon, vehicles with flotation tires	Capacity-generally 2.5 to 13.5 m^3.	Low speed. Principal use is field application.
Dewatered		
Truck	Commercial dump truck with watertight box.	High speed. Principal use is road transport. Can be used for field application.
Farm tractor and wagon or manure spreader, vehicles with flotation tires	Watertight box.	Low speed. Principal use is field application.

production. All except forage offer the advantage that heavy metals generally accumulate less in the grain than in the leaves.

Sludge should be applied to cereal, corn and oil seed land prior to planting or after harvest. Sludge injection into row crop land is possible early in the growing season but precautions are required to avoid soil compaction and root damage.

Forage offers greater flexibility for sludge application than other crops but sludge should be applied only after thorough grazing or harvest and before appreciable regrowth has occurred. Where sludge is surface applied, grazing should be delayed to avoid pathogen transfer to animals. However, there is disagreement concerning the required length of the delay. In Ontario delays of two months for cattle and horses and six months for sheep and swine are recommended (OMAF/OMOE, 1981). In Wisconsin

TABLE 57 SLUDGE APPLICATION METHODS (White, 1976)

Sludge State and Transport Equipment	Characteristics	Comments
Liquid (Surface Application)		
Tank truck	Capacity-2.5 m^3 to maximum allowed on road.	Pressure discharge preferred.[a] Land slope not to exceed 9%. Immediate incorporation preferred.[b]
Farm tractor and tank, wagon, vehicles with flotation tires	Capacity-generally ≤ 13.5 m^3.	Pressure discharge preferred. Land slope not to exceed 9%. Immediate incorporation preferred.
Liquid (Subsurface Application)		
Subsurface injection equipment	Capacity generally ≤ 13.5 m^3. Sludge placed in channel opened by tillage implement.	Conserves sludge nitrogen. Pressure discharge preferred. Vehicles should not traverse injection area for at least one day. Unsatisfactory sludge coverage if soil wet, very hard or frozen.
Solid (Surface Application)		
Truck mounted or farm spreaders	Capacity generally ≤ 15 m^3.	Land slope not to exceed 9%. Immediate incorporation preferred.

[a] Pressure discharge of sludge is preferred to facilitate uniform field application.

[b] Immediate sludge incorporation into soil is preferred to prevent loss of ammonium nitrogen by volatilization.

delays of two months for dairy cows and two weeks for other animals are recommended (Keeney et al., 1975) and in England delays of three weeks and five weeks, respectively, are recommended for dairy cows whose milk is pasteurized and not pasteurized (Alderslade, 1981). In Alberta, a delay of three years is recommended for all animals (Alberta Environment, 1982). The primary purpose of the extended delay is to avoid nitrate poisoning (discussed below) but it also avoids pathogen transfer. Considering the wide diversity of recommendations and a lack of evidence for disease transmission to animals or humans resulting from land application of stabilized sludge, it appears that a delay of six weeks to two months between spreading and grazing or harvest is adequate.

Cereals require smaller amounts of nutrients than corn and forage crops and are subject to lodging if too much nitrogen is supplied.

Forage and silage crops can be hazardous to livestock if nitrate nitrogen in the plant tissue exceeds 3 mg/g dry weight. This might occur in Alberta where one sludge application can supply 450 kg/ha of plant-available nitrogen; however, it is unlikely to occur in Ontario where the upper guideline limit is 135 kg/ha of plant-available nitrogen. In Alberta, the greatest danger is presented by first-crop plant material following sludge application, newly-emerging plant material and hail-damaged, immature cereal crops, especially oats.

Considerable controversy surrounds sludge application to land used for vegetable and fruit production. In Alberta, sludge application to vegetable and fruit land is not recommended. Similarly, Del Monte Corporation in the United States, the largest canners of fruits and vegetables in the world, decided early in 1980 not to accept produce from sludge treated land (Newkumet, 1980). Lack of evidence that sludge application to land used to grow crops for human consumption is totally safe was cited as justification for the Del Monte decision. However, in Ontario sludge application to vegetable and fruit land is permitted subject to constraints. Vegetable crops may not be grown within 12 months following sludge application and sludge may not be applied to fruit land within three months preceding harvest. The United States Environmental Protection Agency, Food and Drug Administration, and Department of Agriculture have prepared a statement of federal policy and guidance for "Land Application of Municipal Sewage Sludge for the Production of Fruits and Vegetables" (1981) which permits controlled application. Evidence is lacking for human health problems resulting from stabilized sludge application to vegetable and fruit land and it appears that controlled application is an acceptable practice.

8.4.8 **Heavy Metals.** Detailed information concerning heavy metals in sludge applied to agricultural land is presented in Sections 4, 5 and 6 of this manual; a summary of information follows.

Because municipal wastewater sludges typically contain much larger concentrations of heavy metals than agricultural soils (Table 58), there is concern that sludge utilization will increase the heavy metal concentrations in soil and have deleterious effects on crops and animals. Recently, extensive research effort has been conducted to determine the fate and effects of sludge metals in soil. Heavy metals concentrations in soils and crops have been monitored, heavy metal chemistry in soil and uptake by plants

TABLE 58 COMPARISON OF HEAVY METAL CONCENTRATIONS (mg/kg, dry wt) IN AGRICULTURAL SOIL AND MUNICIPAL SLUDGE

	Mean for Uncontaminated Ontario soils (OMOE/OMAF, 1981)	Ontario Sludges (OMOE, 1977)	
		Median	Range
Cadmium	0.8	10	5-260
Zinc	55	1600	400-5130
Copper	25	970	280-2570
Nickel	16	120	23-410
Lead	15	375	200-1280
Chromium	15	530	100-9740
Cobalt	5	9	1-42
Molybdenum	2	12	7-97
Mercury	0.1	2.1	0.4-4.7

has been studied, animal feeding trials have been conducted, and modelling to predict human health effects has been undertaken. These studies are ongoing and there is not unanimous agreement concerning the interpretation of results; however, it appears that controlled application of sludge on agricultural land presents little environmental health hazard due to heavy metals.

Heavy metals added to soil are only slightly soluble and, for all practical purposes, remain in the zone of sludge incorporation. Hence, there is a potential for buildup with repeated sludge applications. They participate in precipitation, adsorption and chelation reactions and are found associated with aluminosilicate minerals, iron, aluminum and manganese hydrous oxides and organic matter in soil (Section 4.3).

Heavy metal concentrations in crops depend upon a number of sludge, metal, plant and soil factors. Arsenic, cobalt, mercury, molybdenum, and selenium concentrations in Canadian sludges generally are very low and have no significant effect on plant composition. Arsenic, chromium, lead and mecury may accumulate in the roots of plants but are not translocated to the above-ground material. Copper exhibits limited translocation and seldom occurs at concentrations greater than 20 mg/kg dry weight in above-ground plant material. Cadmium, zinc and nickel exhibit appreciable uptake by plants and generally increase with increasing amounts of metal applied to soil in sludge. However, large differences in the concentrations of these metals may also be related to different plant species, different plant parts and year to year variations. Leafy vegetables usually exhibit larger concentrations than field crops, and vegetation usually exhibits larger concentrations than fruits and seeds. Soil pH is the most important soil factor affecting plant uptake of cadmium, zinc and nickel. Other factors being equal, uptake decreases as soil pH increases to about 7. Soil texture, cation exchange capacity, and organic matter content may also affect uptake of these metals.

In summary, arsenic, chromium, cobalt, lead, mercury, molybdenum and selenium in Canadian sludges utilized on agricultural land are not likely to present a significant environmental health hazard. Although copper, zinc and nickel buildup in the soil may result in phytotoxicity and reduced crop yields, toxicity to animals is very unlikely. In general, animals have high tolerances for these metals and apparently healthy crops do not present a hazard. Notable exceptions are copper toxicities to sheep and possibly cattle which are associated with very low molybdenum intake. Cadmium is the sludge metal of greatest concern because its buildup in soil may result in toxicity to both crops and animals. It is taken up by crops and accumulates in the liver and kidneys of animals. There is concern that healthy crops with enhanced cadmium concentrations might contribute to toxicity, particularly in humans. Humans have a long life span during which accumulation can occur.

It is generally agreed that heavy metal additions to soil in sludge must be regulated to protect soil productivity and maintain crop quality for human and animal food. Moreover, maximum permissible heavy metal contents have been defined for sludges applied to agricultural land in an effort to increase sludge application site life and encourage metal recovery from industrial effluents. Heavy metal guidelines for land utilization of sludge differ between jurisdictions as illustrated in Table 59. The reader is advised to obtain guidelines for his or her area from the appropriate regulatory agency, identified in Appendix A.

8.4.9 Toxic Organics. With the exception of polychlorinated biphenyls (PCBs), very little is known about toxic organic chemicals in wastewaters and sludges. Most toxics research to date has been directed toward determining the fate and effects of heavy metals. However, the Canadian Environmental Protection Service and the United States Environmental Protection Agency recently have generated lists of more than 100 organic chemicals of concern. Research programs have been initiated to develop methods for analysing these chemicals in environmental samples and to determine their fate and effects in the environment.

TABLE 59 COMPARISON OF HEAVY METAL GUIDELINES FOR LAND UTILIZATION OF SLUDGE IN CANADA (Alberta Environment, 1982; OMAF/OMOE, 1981; Standish, 1981)

Jurisdiction	Cd	Zn	Cu	Ni	Pb	Mo
	Minimum acceptable nitrogen to heavy metal ratios in sludge					
Alberta, Total N:metal	1500	10	15	100	20	—
Ontario, $(NH_4 + NO_3)$-N:metal	500	4	10	40	15	180
	Maximum permissible heavy metal concentrations (mg/kg dry weight) in sludge and sludge-based commercial products containing $\leq$ 5% nitrogen.					
Agriculture Canada	20	1850	—	180	500	20
	Maximum permissible heavy metal loadings (kg/ha) to soil*					
Alberta	0.8-1.5	150-300	100-200	12-25	50-100	—
Ontario	1.6	330	150	32	90	4
Agriculture Canada	4	370	--	36	100	4

* Permissible metal loadings to Alberta soils vary with site suitability for sludge application.

Total PCBs in ten Ontario sewage sludges and in soils and crops from agricultural land on which the sludges had been spread were measured (Webber et al., 1983). Small concentrations of PCBs ($\leq$ 1.6 mg/kg dry weight) were observed in the sludges. Application to land caused significant small increases in the PCB contents of soils at four sites but there was no evidence for PCB uptake by crops. Preliminary survey data (Table 51) indicated that Canadian municipal sludges contain generally small amounts of other toxic organic chemicals.

8.4.10 **Pathogens.** Detailed information concerning pathogens in sludge applied to agricultural land is presented in Section 5.

Raw wastewaters contain a variety of pathogens, including bacteria, viruses, parasites and fungi, many of which survive wastewater treatment and are concentrated in the sludge. Although stabilization processes such as aerobic and anaerobic digestion reduce the numbers of pathogens in sludge, there is evidence that some survive and it is thought that they may represent a hazard to human and animal health. There is no known evidence of disease transmission following land application of stabilized sludge; however, precautions to minimize risk, such as delay of grazing and vegetable production, are recommended by most sludge utilization guidelines.

After surviving sewage treatment and exposure to environmental stresses, the pathogens in sludge must be capable of producing disease to present a health hazard. It is considered that Salmonella spp. and Taenia saginata are the pathogens most likely to present such a hazard in Canada (Section 5.4).

8.4.11 Application Rates and Other Limitations. Sludge is a low grade fertilizer material containing significant amounts of nitrogen and phosphorus. It is generally agreed that it should be applied to agricultural lands at rates to make efficient use of these nutrients and avoid groundwater contamination. For example, in Ontario it is recommended that the ammonium plus nitrate-nitrogen loading to land in sludge must not exceed 135 kg/ha (OMAF/OMOE, 1981). This amount of nitrogen approximates the annual requirement for corn production and may be applied once every five years in one or more sludge applications. In Alberta, recommended ammonium plus nitrate-nitrogen loadings to land in sludge range from 100 to 450 kg/ha depending upon sludge type and site suitability (Alberta Environment, 1982). To promote efficient use of the phosphorus fertilizer value of sludge, application to land with $\geq$ 60 mg/kg of sodium bicarbonate extractable (i.e., plant-available) phosphorus in not permitted in Ontario.

Two methods of sludge application on agricultural land are acceptable. They are subsurface injection into soil and surface application followed, as soon as is feasible, by incorporation (tillage) into the soil. Subsurface injection is the preferred application method because it greatly reduces the potential for runoff contamination, odour and aesthetic nuisance and evaporative loss of nitrogen. Sludge application should be uniform and at the recommended rate to insure optimum crop growth and farmer satisfaction.

Sludge application to ice-covered, snow-covered or frozen soils is not recommended due to the potential for runoff contamination; however, it may be permissible where the risks of runoff and flooding have been determined to be minimal (OMAF/OMOE, 1981).

8.4.12 Performance and Monitoring. Regular monitoring of land application systems is necessary to evaluate performance and to determine environmental effects. It should be conducted to protect the land owner, the public and the environment.

Regular sludge analysis is required to determine that the sludge remains acceptable for land application and to maintain a record of nutrient and metal additions to the soil. Sludges should be analyzed for ammonium plus nitrate-nitrogen, total nitrogen, total phosphorus and total heavy metals.

Periodic field inspections are advisable during sludge application. They serve as a check on the sludge hauler and on field operations. The inspector should check the uniformity of sludge spreading and the effect of spreading equipment on soil physical properties. Excessive wheel rutting and soil compaction indicate that spreading should be discontinued until the load-bearing capacity of the soil has increased.

Soil sampling and analysis should be conducted prior to and at intervals during the life of a sludge application site. The initial monitoring is necessary to establish background levels of nutrients and heavy metals in the soil. Subsequent monitoring serves as a check on these constituents in the soil and ensures that recommended maximum loadings are not exceeded.

Heavy metal concentrations in soil are likely to be variable where sludge has been land applied by subsurface injection. This technique places the sludge in discrete furrows rather than mixing it evenly throughout the plow layer. Consequently, care should be taken to ensure that soil samples taken for analysis represent the whole plow layer. Each sample should be a composite of at least 20 subsamples taken according to a predetermined grid pattern from an approximately one-half hectare area.

In the semi-arid regions of Canada, additional soil testing for sodium adsorption ratio, plant-available boron, and electrical conductivity may be advisable to determine whether sodium, boron and soluble salt buildup is occurring in the soil.

Since plants integrate the various soil and environmental factors affecting their growth, plant yield and composition provide the most sensitive and accurate assessment of how municipal sludge affects nutrient and heavy metal availabilities in soil. Plants should be analyzed for total heavy metals and the values compared with data for the same crop grown on a nearby control (no sludge applied) site or with reference control data. Plant monitoring should not be necessary if sludge and soil monitoring indicate that land application has been conducted according to the Alberta or Ontario guidelines. However, if sludge has not been applied according to these or similar guidelines, plant monitoring is advisable.

8.5 Utilization on Forest Land

Although sludge utilization on forest land is not practiced at present in Canada, it is receiving consideration here and elsewhere. A review of the nutrient value, operating requirements and limitations of sludge application for regenerating forest land has been prepared in Nova Scotia (Ogden et al., 1979). Dominion Textiles Incorporated of Magog, Quebec, has proposed spreading sludge on forest land and Du Pont Limited of Maitland, Ontario, has undertaken a lysimeter study to determine environmentally acceptable loading rates of sludge for hybrid poplar culture. Studies of sludge utilization on forest land have been conducted at several locations in the United States (Sopper and Kerr, 1979).

Sludge utilization on forest land offers several advantages over utilization on agricultural land. Forest products are not consumed by humans and there is little, if any, risk of heavy metal and other toxic chemical accumulation in the food chain. Forests are perennial and the application schedule is likely to be more flexible than for agronomic crops. Forest soils are frequently coarse and infertile and may benefit greatly from the nutrients and organic matter contained in sludge. Disadvantages include remoteness, rugged terrain, uneven sludge distribution particularly in established stands, and rapid soil drainage, presenting a high potential for nitrate-nitrogen contamination of groundwater. Sludge application in conifer stands is not recommended in the Netherlands due to increased soil pH, mineralization of soil organic matter and danger of root rot (van den Berg, 1978).

Although heavy metals in sludge may exhibit no adverse effects on tree production they may reduce the quality of understory vegetation as forage for wildlife. The majority of forest soils in Canada are acidic which would favour increased heavy metal solubility and uptake by plants. No data are available on this subject and caution is advised. Pending further information, it is recommended that the same maximum heavy metal loadings be observed for forest as for agricultural lands.

Fertilization has been very restricted in Canadian forests, mainly for economic reasons. However, it is used routinely in nurseries, seed orchards and the Christmas-tree industry. Recent increases in commercial fertilizer costs should increase the desirability of sludge as a fertilizer substitute for these industries.

8.6 Utilization for Land Reclamation and Revegetation

Large areas of land are disturbed annually by man in his quest for minerals, coal and other resources. In the past, little effort was made to reclaim disturbed land; however, current environmental consciousness dictates that it should be restored as nearly as possible to the original condition. This usually involves revegetation with forage species and trees.

Reclamation of disturbed land is generally difficult because factors such as low levels of nutrients, insufficient soil organic matter, lack of a soil biological community, unsuitable physical and chemical properties, and steep slopes subject to erosion and slides may limit vegetation establishment and growth. Conventional reclamation methods involve grading the surface of disturbed areas into slopes that minimize erosion and facilitate planting. Topsoil is rarely applied. Soil amendments such as lime and fertilizer are applied and a crop is planted. Generally a mulch is applied to conserve moisture.

Stabilized sewage sludge is beneficial for land reclamation because it is a slow release fertilizer material that contains sufficient nutrients, except for potassium, for plant growth. Sludge contains about 50% organic matter (dry weight basis) and improves the physical and chemical properties of disturbed soils. It improves water infiltration and retention and reduces surface crusting and compaction. Sludge containing lime can substantially increase the pH of acid mine spoil and improve leachate quality by reducing the concentrations of iron, aluminum and sulphate. Another attractive feature is that sludge is available in quantity at low or no cost from large municipalities. Several potential disadvantages include bulkiness and difficult handling properties, high transportation costs, groundwater contamination especially with nitrate-nitrogen, and the presence of pathogens and heavy metals.

Canadian guidelines for land reclamation with sludge have not been developed but it is suggested that the same maximum heavy metal loadings be observed as for agricultural lands. To establish vegetation it may be necessary to apply an initial large sludge dressing rather than repeated small dressings over several years. A large sludge dressing may cause nitrate contamination of groundwater but this effect is unlikely to persist for more than a few months and it has been suggested that the short-term disadvantage of groundwater contamination is far outweighed by the long-term benefits of revegetation.

8.7 Sludge Disposal

8.7.1 Landfills. Sludge landfilling may be defined as the application of sludge to land and subsequent covering with a layer of soil at least 20 cm deep. Landfilling may be a cost-effective disposal option in cases where the sludge is of unsuitable quality for land application or where there is inadequate agricultural land available for utilization. The environmental impact of landfilling is confined to the site. Disadvantages of landfilling include potential operational problems (i.e., leachate management and gas hazards), limited life of the site, and increasing difficulty in finding new sites and receiving approval. Although new technologies using trenching have reduced some of the containment and leachate problems, landfill sites are suitable only for recreational purposes after surface restoration.

Although not always required, stabilization and dewatering of sludge is recommended for landfill disposal. Stabilization reduces the odour potential associated with landfilling and dewatering improves operation and reduces leachate and surface runoff related problems.

Sludge landfill methods can be grouped into three general categories: sludge-only trench fill, sludge-only area fill, and co-disposal with refuse. A detailed discussion of sludge landfilling is presented in the U.S. EPA Technology Transfer "Process Design Manual, Municipal Sludge Landfills" (U.S. EPA, 1978).

The sludge-only trench method involves excavating trenches, so that dewatered sludge may be entirely buried below the original ground surface. This method has been used with both stabilized and raw sludges but daily cover is required. Prior dewatering is not essential but will considerably improve ease of operation.

In the sludge-only area fill method, the sludge is mixed with soil and the mixture is placed on the original ground surface. Stabilized and dewatered sludge is best suited for this method, since daily cover is not usually provided. Solids content should be $\geq$ 15% by weight to support cover material.

Co-disposal of sludge with municipal refuse is the most common sludge landfilling method. The sludge and refuse are thoroughly mixed before they are spread, compacted and covered with soil. The sludge should be stabilized and dewatered to a solids content of $\geq$ 15%. Liquid sludge may be used as long as the absorptive capacity of the refuse is not exceeded.

Site selection depends upon the type of landfill operation proposed but the following factors should be considered:

- haul distance and accessibility;
- land-use zoning restrictions;
- environmental sensitivity;
- topography;
- soil type; and
- depth to groundwater table, etc.

8.7.2 Dedicated Disposal Sites. Dedicated land disposal involves the application of heavy sludge loadings to some finite area of land that has been set aside for all time for the disposal of wastewater sludge. Public access must be severely limited because of potential pathogen contamination of the site. Ownership of the site is extremely critical since long-term buildup of heavy metals, and toxic chemicals in the soil will make it unsuitable for virtually any future use. Ownership and complete control of the site is preferably the responsibility of the operating authority. Site design and management must provide for groundwater and surface water protection from migrating pollutants. As with other land disposal options, dedicated land disposal usually requires the sludge to be stabilized prior to application to ensure odour control. Dewatering is generally also a prerequisite.

8.8 Cost of Land Application of Sludge

Although costs to a municipality for the land application of sludge vary greatly and may frequently appear quite high on a dry solids basis, land application is frequently the only viable option for the small-to-medium sized municipality.

An examination of Ontario sludge haulage costs for 1973 (Black and Schmidtke, 1974) determined a range of values from $21 to $275 per tonne dry solids with an arithmetic average of $32. Costs for landfilling of sludge, including dewatering, ranged from $10 to $50 per tonne dry solids. These costs compare to incineration costs of $25 to $90 per tonne.

With land application of liquid sludge, the major cost is transportation. Truck transport is the least expensive for one way distances of $\leq$ 32 km and sludge volumes of 38 000 to 57 000 m^3 per year. Pipelines are least expensive when the annual sludge volume is 110 000 to 260 00 m^3. Trucking provides flexibility and is not capital intensive if trucks are leased or haulage is by contract (U.S. EPA, 1979).

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GLOSSARY

absorption - the molecules of one phase interpenetrate nearly uniformly among those of another phase to form a solution.

acclimated microorganisms - any population of microorganisms that is adapted to certain environmental conditions.

activated sludge - a biological wastewater treatment process that requires mixing of bacteria and the organics in wastewater in an aerated chamber; a settleable sludge is produced.

adsorption - the binding of dissolved ions or compounds on the surfaces of solid substances such as clay and humus particles.

advanced waste treatment - any treatment, biological, chemical or physical, that achieves removal of nutrients and/or soluble species not adequately removed by a secondary treatment process, while still attaining the suspended solids and organics removals of secondary treatment.

aerosol - a gaseous suspension of ultra-microscopic particles of a liquid; particles are in the size range of 0.01 to 50 micrometres.

ammonification - the biochemical process whereby ammonia nitrogen is released from nitrogen-containing organic compounds.

assimilation - the conversion of inorganic forms to organic forms within living tissue.

available water capacity (AWC) - that amount of water which is held in the soil between field capacity and the permanent wilting point, and is available for plant use.

bacteria - one-celled plant-like organisms; they require soluble food and reproduce by binary fission.

biodegradation - the breakdown, by microorganisms, of complex organic compounds in a substance to their constituent elements or compounds.

BOD_5 - five-day biochemical oxygen demand; a measure of the amount of dissolved oxygen required to meet the metabolic needs of aerobic microorganisms which assimilate the organic matter available to them in a water sample; test performed with microorganisms acclimated to the sample material for 5 days at 20°C.

bulk density - the mass of dry solid material (such as soil) per unit of volume.

cation exchange capacity (CEC) - a measure of the ability of the soil to retain cations.

chelate - a molecular structure in which a heterocyclic ring is formed by the unshared electrons of neighbouring atoms.

coliform bacteria - all aerobic and facultative anaerobic, non spore-forming, gram-stain negative rods that ferment lactose with gas production within 48 hours at 35°C.

COD - chemical oxygen demand; the oxygen equivalent of that portion of organic matter in a sample susceptible to oxidation by a strong chemical oxidant.

colloid - organic and inorganic matter in the soil with very small particle size and a correspondingly large surface area per unit mass.

colloidal soil particles - clay and humus fraction of a soil characterized by their extremely small size ($\leq$0.002 mm), very high ratio of surface area to volume, and the presence of a negative electrical charge.

cyst - a protective organism structure with a distinct wall; many microorganisms form cysts under adverse environmental conditions; these cysts may contain either the egg, the immature organism, or the mature organism. Some pathogens are transmitted primarily by being released as cysts which are then ingested by the new host.

dew point - the temperature at which air becomes saturated when cooled without addition of moisture or change of pressure.

denitrification - the biochemical reduction of nitrate and nitrite to gaseous nitrogen either as molecular nitrogen or as an oxide of nitrogen; brought about in the absence of molecular oxygen by denitrifying bacteria.

electrostatic bond - a chemical bond in which two atoms are kept together by forces caused by transferring one or more electrons from one atom to the other.

enteric - of or within the intestine; enteric bacteria are microorganisms found in the intestinal tract of humans and animals.

epidemic - a sudden increase in the incidence rate of a disease to a value above normal, affecting large numbers of people and spread over a wide area.

epidemiology - the study of the mass aspects of disease.

evapotranspiration - the combined loss of water from an area by evaporation from soil, water and plant surfaces and transpiration (release of vapour) from plants.

eutrophication - a natural aging process of lakes whereby aquatic plants become abundant and dissolved oxygen becomes deficient; usually accelerated by introduction of nutrients such as nitrogen and phosphorus from outside sources.

fecal coliforms - the type of coliform bacteria present in virtually all fecal material produced by mammals. One of the common kinds of fecal coliforms is Escherichia coli (E. coli). Since fecal coliforms are usually not pathogens, they only indicate the potential presence of human disease organisms.

field capacity - the moisture content that a soil will hold against the force of gravity after it has drained for 48 hours following saturation; the amount of water retained by the micropores.

filterable solids - that portion of the solids content of a water sample which will pass through a filter and not be volatilized by drying of the collection vessel; also called "filterable residue".

gastroenteritis - inflammation of the mucous membrane of the stomach and intestine, one form of which is called food poisoning. This disease may be caused by organisms which are contained in human wastes and are transmitted by ingestion of contaminated food or water.

groundwater - water that fills all the unblocked pores of underlying material below the water table, which is the upper limit of saturation.

growing season - the period of the year when climatic conditions are favourable for plant growth; specific to a given area.

heavy metal - a metal whose density compared to water is 5.0 or greater.

helminth and helminth ova - a worm, especially a parasitic intestinal worm or its eggs (ova).

horizon (soil) - a layer of soil, approximately parallel to the soil surface, with distinct characteristics produced by soil forming processes.

immobilization - the conversion of an element from the inorganic to the organic form in microbial or plant tissues, rendering the element not readily available to other organisms or plants.

indicator organism - an organism that, when measured in water, indicates pollution or the presence of pathogens but which does not necessarily cause disease in itself. For instance, the presence of fecal coliforms in water indicates that human disease organisms may be present, but coliforms themselves are not usually pathogens.

infiltration - movement of water through the soil surface into the ground; expressed in cm/s, influenced by both permeability and moisture content of the soil.

leachate - water which enters the groundwater by percolating through the soil.

leaching - the removal of materials in solution from the soil.

ligand - the molecule, ion, or group bound to the central atom in a chelate or a coordination compound. Example: the ammoni molecules in $[CO(NH_3)_6]^{+3}$.

macropore space - the total volume of soil pores that are large enough not to hold water against gravity by capillary attraction.

metal methylation - formation of an organo-metallic compound in which the hydrogen of the hydroxyl group (OH^-) of methyl alcohol is replaced by a metal.

micropore space - the total volume of soil pores which are small enough to hold water against gravity by capillary attraction.

mineralization - the conversion of a compound from an organic form to an inorganic form.

MPN - most probable number; a statistical index of bacterial concentration in a water sample.

nitrification - oxidation of ammonium to nitrite and oxidation of nitrite to nitrate by certain bacteria.

nitrogen fixation - the conversion of elemental nitrogen (N_2) to organic combinations or to forms readily usable in biological processes; especially by certain bacteria in the nodules of leguminous plants making the nitrogen available to the plants.

NOD - nitrogen oxygen demand; utilization of free oxygen by certain autotrophic bacteria to oxidize ammonia to nitrite and nitrate, usually occurring from 6 to 10 days after the start of a BOD analysis; also known as second-stage BOD.

overland flow - a method of land application whereby wastewater is applied onto gently sloping, relatively impermeable soil that has been planted to vegetation. Biological oxidation occurs as the wastewater flows over the ground and contacts the biota in the vegetative litter.

pathogen - a disease-producing organism.

PCB - polychlorinated biphenyl; a synthetic organic compound used in several manufacturing processes; persistent in the environment because it resists degradation.

percolation - the downward movement of water through soil.

permanent wilting point - the dividing point between the soil moisture that is extractable by plant roots and the moisture that is held too tightly for plant use.

permeability - the ease with which water and air are transmitted through a unit cross-section of saturated soil in unit time; commonly expressed in cm/s.

PFU - plaque-forming unit; a virus or viruses which form(s) a colony visible as a clear area on a plate of host cells; used as a measure of viral concentration.

phytotoxic - poisonous to plants.

porosity - the fraction of the total volume of soil occupied by channels and pores.

precipitation - any solid or liquid water particles that fall from the atmosphere and reach the ground; also the amount, expressed in terms of depth of liquid water, which has fallen at a given point over a specified period of time.

preliminary treatment - a subset of primary treatment; removal of screenings and grit (readily settleable non-organic matter), without any appreciable removal of the organic fraction of the wastewater.

primary treatment - removal of screenings, grit, grease and floating solids, and readily settleable organic solids from wastewater. Treatment standards usually associate removals of about 50-60% suspended solids and 25-40% BOD with primary treatment.

protozoa - single-celled, usually microscopic organisms of the phylum or subkingdom Protozoa, which include the most primitive forms of animal life. Many are capable of forming cysts which are excreted by the host and may resist waste treatment processes.

rapid infiltration system - a method of land application whereby large volumes of water are applied to the land, infiltrate the surface, and percolate through the soil pores; suitable for soils with high permeability.

regolith - the unconsolidated mantle of earth above the bedrock resulting from weathering of the underlying rock and/or decomposition of material transported by gravity, wind, water, or ice.

secondary treatment - the application of biological treatment processes, usually an activated sludge or attached growth microbial reactor along with secondary settling, following a primary treatment system. Removals of 85-90% BOD and suspended solids are commonly associated with secondary treatment.

septic - characterized by anaerobic breakdown of proteins by certain bacteria, resulting in foul-smelling end products.

sodium adsorption ratio (SAR) - a ratio of available sodium, calcium and magnesium in the soil solution which can be used to indicate whether or not the accumulation of sodium in the soil exchange complex will lead to a degradation of soil structure.

soil - in a rigorous sense, the upper portion of the regolith which has been intensely altered by living organisms and climate, giving rise to distinct layers called horizons. In waste treatment, soil refers to the entire regolith.

soil aggregates - clumps of soil particles which form units that range from weak to stable, small to large, and simple to complex.

soil complex - a mapping unit used in detailed soil surveys where two or more defined soil taxonomic units are so intimately intermixed geographically that it is undesirable or impractical, because of the scale being used, to separate them.

soil moisture tension - the equivalent negative pressure in the soil water, equal to the pressure that must be applied to the soil water to bring it to hydraulic equilibrium through a porous permeable membrane, with a pool of water of the same composition.

soil series - the basic unit of soil classification, being a subdivision of a family and consisting of soils that are essentially alike in all major profile characteristics.

soil structure - the organization of individual particles into clumps or aggregates.

soil survey - the systematic examination, description, classification, and mapping of soils in an area. Soil surveys are classified according to the kind and intensity of field examination.

soil texture - the coarseness or fineness of the individual mineral particles in soil.

soil type - the lowest unit in the natural system of soil classification; a subdivision of a soil series consisting of or describing soils that are alike in all characteristics including texture of the A (surface) horizon.

solubility product constant (K_{sp}) - a constant expressed as the product of the molar concentrations of ions in equilibrium with their electrolyte, or combined form.

specific adsorption - the retention of certain cations and anions so tightly by the soil that they are not exchangeable with other cations and anions. Specific adsorption occurs between ions or compounds in solution and the solid colloidal phase.

substrate - source of nutrients used by a microbial population for biological synthesis.

suspended solids - that portion of the solids content of a water sample which will not pass through a filter; also called "non-filterable residue".

TKN - total kjeldahl nitrogen; concentration of ammonia plus organically bound nitrogen in a water sample.

TOC - total organic carbon; a measure of carbon contained in organic constituents of a water sample.

transmissibility - usually called transmissibility coefficient, the volume of water per day that percolates through each unit area of water-bearing bed for each unit thickness of bed.

unit process - a treatment unit which uses chemical, physical or biological mechanisms as the basic means of treating wastewater.

vector - an agent, such as an insect, capable of mechanically or biologically transferring a pathogen from one organism to another. A mosquito that carries organisms that cause malaria is such a vector.

virus - an infectious agent ranging in size from 10 to 20 nanometres in diameter, composed of a protein sheath surrounding a nucleic acid core, capable of infecting specific living organisms and having the ability to replicate inside a living cell; characterized by total dependence on living cells for reproduction and by lack of independent metabolism.

volatilization - the process of vaporizing or becoming gaseous.

APPENDIX A

PROVINCIAL AGENCIES INVOLVED IN LAND APPLICATION SITE REVIEW

APPENDIX A PROVINCIAL AGENCIES INVOLVED IN LAND APPLICATION SITE REVIEW

		Status of Guidelines	
Province	Agency	Treated Wastewater	Sludge
Alberta	Alberta Environment Standards and Approvals Div. 9820 - 106 Street Edmonton, Alberta T5K 2J6	A Practical Guide to Municipal and Wastewater Irrigation, Discussions and Guidelines, 1977.	Guidelines for the Application of Municipal Wastewater Sludges to Agricultural Lands, 1981.
British Columbia	Ministry of Environment Waste Management Branch Victoria, British Columbia V8V 1X5	Pollution Control Guidelines for Municipal Effluent Application to Land, Jan. 1981.	Guidelines for use with the Regulations under the Waste Management Act for Control of the Discharge of Sludge to Land, 1982 (draft).
Manitoba	Manitoba Dept. of Consumer and Corporate Affairs and Environment Environmental Control Services Bldg 2, 139 Tuxedo Avenue Winnipeg, Manitoba R3N 0H6		Order No. 921 of the Manitoba Clean Environment Commission under the Clean Environment Act, 1981. Regulation for land application of Manitoba sludge.
Ontario	Ministry of the Environment Wastewater Treatment Section 135 St. Clair Avenue West Toronto, Ontario M4V 1P5	Pollution Control Guidelines for Municipal Effluent Application to Land, 1981.	Guidelines for Sewage Sludge Utilization on Agricultural Lands, 1981.
Quebec	Ministère de l'Environnement 2324, Dalton, 1er étage Sainte-Foy, Quebec G1P 3S3		
Newfoundland	Department of Environment Elizabeth Towers Elizabeth Avenue St. John's, Newfoundland A1B 3X9		
New Brunswick	Environment New Brunswick P.O. Box 6000 Fredericton, N.B. E3B 5H1	Guidelines for the Collection and Treatment of Wastewater 1979.	
Nova Scotia	Nova Scotia Dept. of the Environment P.O. Box 2107 Halifax, Nova Scotia B3J 3B7		Guidelines for Utilization of Digested Sludge on Agricultural Lands in Nova Scotia, 1983 (draft).
Prince Edward Island	Department of Community Affairs P.O. Box 2000 11 Kent Street Charlottetown, P.E.I. C1A 7N8		
Saskatchewan	Saskatchewan Environment Water Pollution Control Branch 1855 Victoria Avenue 5th Floor Regina, Saskatchewan S4P 3V5		Application of Municipal, Sewage Sludge to Land - Interim Guidelines, 1983 (draft).
Northwest Territories	Northwest Territories Water Board P.O. Box 1500 Yellowknife, N.W.T. X1A 2R3	Guidelines for Municipal Type Wastewater Discharges in the Northwest Territories, 1981.	
Yukon	Yukon Territory Water Board 2000 - 4114 - 4th Avenue Whitehorse, Yukon Y1A 4NT	Guidelines for Municipal Wastewater Discharges in the Yukon Territory, 1983.	

APPENDIX B

IRRIGATION WATER QUALITY CRITERIA

APPENDIX B - IRRIGATION WATER QUALITY CRITERIA

A good quality irrigation water has the potential to allow maximum yield under good soil and water management practices. However, with poor quality water, soil and cropping problems can be expected to develop and yields to be reduced unless special management practices are adopted to maintain or restore maximum productivity. As no criteria for wastewater used for irrigation presently exist, it is necessary to introduce water quality standards for conventional irrigation practices.

B.1 Conventional Irrigation Water Quality

A universal statement of criteria for irrigation water quality does not exist. Most states in the U.S.A. and provinces in Canada have developed their own standards. These standards have been developed with respect to local conditions, experiences and irrigation demand. Most standards, however, are based on modifications of those outlined by the U.S. Salinity Laboratory (U.S.D.A. Handbook 60, 1954), and by refinements presented by Ayers and Westcot (1976)*. Guidelines (Table B-1) and pertinent excerpts from Ayers and Westcot appear below. Several basic assumptions have been made in developing the guidelines in Table B-1.

1) Use of Water: The soil texture is sandy loam to clay loam, with good internal drainage. The climate is semi-arid to arid where effective annual rainfall is low. These guidelines may need adjustment for areas where there are large amounts of precipitation during part of the year.
2) Methods and Timing of Irrigation: Surface and sprinkler methods of irrigation are assumed, including flood, furrow, corrugations and sprinklers, or any other system that applies water on an "as needed" basis. This assumes that the crop utilizes a considerable portion of the stored soil water before the next irrigation. With these irrigation methods about 15% of the applied water is assumed to percolate below the rooting depth.
3) Uptake of Water by Crops: Uptake of water by the crop takes place from wherever water is most readily available in the rooting zone. This is normally about 40% from the upper one-quarter of the root zone, 30% from the second quarter, 20% from the third quarter, and 10% from the lowest quarter. Each irrigation will leach the upper soil area and maintain it at a relatively low salinity.

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* R.S. Ayers and D.W. Westcot, "Water Quality for Agriculture", Irrigation and Drainage Paper No. 29, Food and Agriculture Organization, Rome, 1976.

TABLE B-1 GUIDELINES FOR INTERPRETATION OF WATER QUALITY FOR IRRIGATION (AYERS AND WESTCOT, 1976)

	Degree of Problem		
Irrigation Problem	No Problem	Increasing Problem	Severe Problem
SALINITY (affects crop water availability) ECw (dS/m)	< 0.75	0.75 - 3.0	> 3.0
PERMEABILITY (affects infiltration rate into soil)			
ECw (dS/m)	> 0.5	0.5 - 0.2	< 0.2
Adj. SAR[a]			
Montmorillonite (2:1 crystal lattice)	< 6	6 - 9[b]	> 9
Illite-Vermicultie (2:1 crystal lattice)	< 8	8 - 16[b]	> 16
Laolinite-sesquioxides (1:1 crystal lattice)	< 16	16 - 24[b]	> 24
SPECIFIC ION TOXICITY (affects sensitive crops)			
Sodium[c] (adj. SAR)	< 3	3 - 9	> 9
Chloride[c] (meq/L)	< 4	4 - 10	> 10
Boron (mg/L)	< 0.75	0.75 - 2.0	> 2.0
MISCELLANEOUS EFFECTS (affect susceptible crops)			
NO_3-N or NH_4-N (mg/L)	< 5	5 - 30	> 30
HCO_3 (meq/L) (overhead sprinkling)	< 1.5	1.5 - 8.5	> 8.5
pH	(Normal Range 6.5 - 8.4)		

[a] "adj. SAR" means adjusted Sodium Adsorption Ratio. Values presented are for the dominant type of clay mineral in the soil since structural stability varies between the various clay types.

[b] Use the lower range if ECw < 0.4 mS/cm.
Use the intermediate range if ECw = 0.4-1.6 mS/cm.
Use upper limit if ECw > 1.6 mS/cm.

[c] Most tree crops and woody ornamentals are sensitive to sodium and chloride (use values shown). Most annual crops are not sensitive. With sprinkler irrigation on sensitive crops, sodium or chloride in excess of 3 meq/L under certain conditions has resulted in excessive leaf adsorption and crop damage.

Water quality and drainage problems are very often interrelated and adequate control of a potentially damaging water table is recognized as an essential requirement for successful long-term irrigated agriculture. A definition of degree of problem is also necessary.

Degree of Problem: The division of Table B-1 into "No Problem", "Increasing Problem" and "Severe Problem" is somewhat arbitrary since changes occur gradually and there is no clear-cut breaking point. Changes of 10 to 20% above or below the values shown may have little significance if considered in proper perspective with other factors affecting yield. Ordinarily no soil or cropping problem due to water quality will be experienced with water having the values shown for "No Problem" in Table B-1. On the other hand, if water is used which equals or exceeds the values shown for the "Severe Problem", soil or cropping problems will commonly be experienced. With intermediate water quality values a gradually "Increasing Problem" would be experienced as the water quality deteriorates.

Specific conditions that may modify these values include the leaching fraction, the conditions of drainage, method of irrigation, the climate and rainfall, physical soil conditions, crop tolerance to salinity and the chemical properties of the soil.

The problems that result from using poor quality water will vary both as to kind and degree but the most common are: 1) salinity; 2) permeability, and 3) toxicity.

B.1.1 **Salinity.** A salinity problem due to water quality occurs if salts from the applied irrigation water accumulate in the root zone and yields are affected. Potential salinity problems caused by irrigation water are evaluated by the guidelines in Table B-1.

With shallow water tables, a salinity problem may also exist due to upward movement of water and salts from the groundwater as the water evaporates from the soil or is used by the crop. Such a salinity problem is related to high water tables and the lack of drainage; it is only indirectly related to salts in the irrigation water and is not included within the evaluation of the guidelines. However, once the drainage problem is solved and the water table stabilized, the guidelines will apply.

Most of the salts added with the irrigation water are left behind in the soil as water is removed by the crop. These may accumulate and reduce the availability of soil water to the crop. To avoid salt accumulation to an excess level, they must be removed in amounts about equal to the salts applied (salt balance concept). To dissolve and remove the salts adequate water must be applied to allow percolation through the entire root zone (leaching).

If a long-term salt balance is achieved by leaching, the average soil salinity of the root zone will be closely associated with the quality of the irrigation water applied as well as with the fraction of water moving through the root zone. If the water management, as locally applied, accomplishes more leaching than assumed, salts will not accumulate to as great an extent, and slightly higher salinity in the irrigation water could be tolerated. If leaching is less, salts will accumulate to a greater extent and salinity problems and yield reductions may be experienced at lower water salinity (EC_W) than the guidelines of Table B-1 indicate.

The major objective in choosing a management procedure to overcome a salinity problem is to improve soil water availability to the crop. Some of the management practices include:

1) irrigate more frequently to increase the soil water supply to the crop;
2) plant crops that are tolerant of an existing or potential salinity problem;
3) routinely use extra water to satisfy the leaching requirement
4) change method of irrigation to one that will give better salt control;
5) change cultural practices.

More drastic practices to improve or restore productivity of salt-affected soils might include:

1) leach as needed to reduce concentration of accumulated salts;
2) improve the uniformity of slope or level of land to allow more uniform water application;
3) modify soil profile to improve downward water percolation, i.e., subsoiling, deep ploughing;
4) establish artificial drainage if water table is a problem;
5) blend saline irrigation water with relatively non-saline water.

B.1.2 **Permeability.** A permeability problem occurs if the water does not enter the soil rapidly enough during irrigation to replenish the soil with water needed by the crop before the next irrigation. Reduced permeability is generally a problem in the upper few centimetres of soil but occasionally may occur at greater depths. Permeability can be affected by many factors other than water quality, including physical characteristics, such as soil texture, layering or stratification, compaction, and chemical characteristics such as type of clay minerals and exchangeable cations. The guidelines in Table B-1 refer to permeability problems as they relate directly to unfavourable changes in soil chemistry. Low salinity and high sodium in the irrigation water are the causes. They do not relate to problems of physical soil characteristics such as texture and compaction.

Low salinity waters are corrosive and tend to deplete surface soils of readily soluble minerals and salts. They have a strong tendency to rapidly dissolve all sources of calcium from the surface soil causing the finer soil particles to disperse, to fill pore spaces and to seal the soil surface. Very low salinity waters (ECw < 0.2 dS/m) often result in soil permeability problems and the lower the ECw, the greater is the potential for problems.

High sodium in the irrigation water can cause a severe soil permeability problem. Meeting the crop water demand under these conditions may become extremely difficult. In addition, other problems such as poor crop germination and soil aeration, and increased disease and weed problems due to surface water ponding and stagnation may require special consideration.

The most commonly used method to evaluate the potential for permeability problems has been the measurement of sodium adsorption ratio (SAR) according to the equation (USDA Handbook 60, 1954):

$$\mathrm{SAR} = \frac{\mathrm{Na}}{\sqrt{\frac{\mathrm{Ca} + \mathrm{Mg}}{2}}}$$

where: Na = sodium in meq/L

Ca + Mg = calcium plus magnesium in meq/L

For SAR values greater than 6 to 9, the irrigation water could be expected to cause a permeability problem on the shrinking-swelling types of soil containing montmorillonite and illite-vermiculite clay minerals (Table B-1)..

Permeability problems, however, are also related to the carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) content in the irrigation water and this is not considered in the SAR procedure.

Recent research has added refinements to the previous concept of SAR. The guidelines in Table B-1 use this new concept which employs a modification of the previous SAR and is called the adjusted sodium adsorption ratio (adj. SAR). The older SAR procedure is modified to include changes in soil water composition that are expected to result from combinations of salts which will either dissolve lime from the soil (adding calcium to the soil water) or deposit of lime in the soil (reducing calcium in the soil water). The adj. SAR is then related to the predominant soil clay mineralogy as shown in Table B-1.

The adj. SAR is calculated using the semi-quantitative equation given below:

$$\text{adj. SAR} = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}} \left[1 + (8.4 - pHc)\right]$$

Methods for calculating adjusted SAR values are outlined by Ayers (1977).*

Since the permeability problem only reduces the volume of water in storage for crop use, there seems little need to take corrective action until either the crop water demand or the leaching requirement can no longer be satisfied. Other problems caused by reduced permeability, however, may force corrective action. Included are problems such as waterlogging, crusting or compaction, poor aeration and germination, excessive weeds and diseases. These may reduce yields as much as an actual water shortage to the crop. Corrective practices available include both "chemical" and "physical" methods.

The suggested practices that maintain or bring about a beneficial change in the soil or water chemistry include:

1) using soil or water amendments (gypsum, sulphur, sulphuric acid, etc.);
2) blending or changing the irrigation water supply.

The physical methods include cultural practices that manipulate the soil to increase infiltration or reduce the rate of water flow over the soil and allow more "opportunity time" for infiltration:

1) irrigate more frequently;
2) cultivation and deep tillage;
3) increase the time allotted (duration) for an irrigation;
4) changing direction of irrigation to reduce grade (slope) of the land;
5) collecting and re-circulating runoff water;
6) with sprinklers, matching rate of water application to soil infiltration rate;
7) using organic residues.

B.1.3 **Toxicity.** A toxicity problem is different from the salinity and permeability problems because toxicity occurs within the crop itself as a result of the uptake and accumulation of certain constituents from the irrigation water and may occur even though salinity is low. The toxic constituents of concern are sodium, chloride or boron. They can reduce yields and cause crop failure.

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* R.S. Ayers, "Quality of Water for Irrigation", J. Irrigation and Drainage Div., ASCE, 193, 1977.

Most tree crops and other woody-type perennial plants are particularly sensitive to low concentrations of sodium. Most annual crops are not so sensitive, but may be affected by higher concentrations of sodium.

Most tree crops and other woody perennial plants are sensitive to low concentrations of chloride while most annual crops are not. However, even the less sensitive crops may be affected at high concentrations of chloride. Chloride is not adsorbed by soils but moves readily with the soil water. Like sodium it is taken up by the roots and translocated to the shoot.

Boron is an essential element for plant growth but is needed in relatively small amounts. In excess, boron becomes toxic. A boron toxicity problem is usually associated with boron in the irrigation water, but may be caused by naturally occurring soil boron. Boron toxicity appears to affect a wide variety of crops while sodium and chloride toxicities were mostly centred on the tree crops and woody perennials.

Toxicity problems occur at relatively low concentrations in the irrigation water. If sensitive crops are to be grown, certain management practices may be needed which either reduce the effective concentration of the toxic substances or make adjustments that improve production under existing concentrations. Practices to reduce the effective concentration of toxic constituents include:

1) irrigate more frequently;
2) use additional water for leaching;
3) in the case of sodium toxicity, use an amendment, such as gypsum or sulphuric acid;
4) change or blend water supplies.

Practices to adjust to existing conditions include:

1) plant tolerant crops;
2) improve water management where this is contributing to the toxicity problem. This may include increasing the leaching fraction, periodic leaching, land grading, profile modification and artificial drainage.

B.2 Considerations for Wastewater Irrigation Guideline Development

The preceding discussion pertains to conventional irrigation, primarily in an arid region, where crop production is paramount. Modifications are necessary when considering wastewater utilization and treatment in Canada. Of primary importance when considering wastewater utilization and treatment are the salinity, SAR, nutrient and heavy metal concentrations as well as the microbiological characteristics of the wastewater involved.

B.2.1 Salinity. Salinity should not be a problem with respect to municipal effluent, as most municipal water supplies are below 1 mS/cm in electrical conductivity. Generally, the dissolved solids contribution due to domestic use is 0.3 dS/m. Therefore, raw sewage salinity levels will be below 1.3 dS/m. Exceptions to this generalization do exist, primarily in the arid regions of Canada, due to the following circumstances:

1) small prairie towns using water with salinity levels above the recommended levels due to the absence of a low salinity water supply;
2) infiltration of saline groundwater into sewage collection lines;
3) evaporation greatly exceeding precipitation where large shallow lagoons are used, thus resulting in a concentration of salts;
4) industries discharging saline water into the municipal system.

Periodic wastewater analysis for salts should be undertaken to identify problems.

B.2.2. Sodium Adsorption Ratio. The sodium adsorption ratio of municipal wastewater is variable. Surface water supplies are low in SAR; however, groundwater can have exceptionally high SAR values, making it unsuitable for irrigation.

The sodium concentration of municipal water can be modified by domestic use (particularly if water softeners are used), infiltration of high sodium groundwater into the collection line, industrial discharges and, concentration by evaporation, and precipitation of calcium in a large lagoon system. For small projects, effluents with a high SAR and low EC can be modified by adding soluble calcium salt to either the effluent or the soil.

B.2.3 Metals. Concern has been voiced that effluent used for land application may contain levels of trace metals which could be toxic to soil organisms, plants and consumers of plant material. A large proportion of the metals in raw wastewater is removed during treatment. Concentrations of trace metals rarely exceed the limits in Table B-2. Treated effluent from municipalities that are heavily industrialized should be subjected to analysis for trace metals on several occasions if land application is being considered.

TABLE B.2 RECOMMENDED MAXIMUM CONCENTRATIONS OF TRACE METALS IN IRRIGATION WATERS (NATIONAL ACADEMY OF SCIENCE, 1974) [a]

Element	For waters used continuously on all soil (mg/L)	For use up to 20 years on fine-textured soils of pH 6.0 to 8.5 (mg/L)
Aluminum	5.0	20.0
Arsenic	0.10	2.0
Beryllium	0.10	0.50
Boron	0.75	2.0-10.0
Cadmium	0.010	0.050
Chromium	0.10	1.0
Cobalt	0.050	5.0
Copper	0.20	5.0
Fluoride	1.0	15.0
Iron	5.0	20.0
Lead	5.0	10.0
Lithium	2.5[b]	2.6[b]
Manganese	0.20	10.0
Molybdenum	0.010	0.050[c]
Nickel	0.20	2.0
Selenium	0.020	0.020
Zinc	2.0	10.0

[a] These levels will normally not adversely affect plants or soils. No data are available for mercury, silver, tin, titanium, tungsten.

[b] Recommended maximum concentration for irrigating citrus is 0.75 mg/L.

[c] Only for fine-textured acid soils or acid soils with relatively high iron oxide contents.

B.2.4 Bacterial Quality. A survey of health regulations by Coerver (1968)* showed that 18 of the responding 37 states of the U.S. had specific regulations or policies for wastewater irrigation. Only one of these states opposed the use of domestic wastewater for irrigation. The remaining 18 prohibited wastewater irrigation of foods that could be eaten raw and six prohibited the irrigation of dairy pastures. According to a literature survey by Parsons et al. (1975),* the range of fecal coliform numbers that various states considered acceptable was 1000 to 10 000 per 100 mL. However, a literature review by the U.S. EPA (1982) showed that the fecal coliform count in wastewater used for irrigation in Canada and the United States exceeded 8000 per 100 mL. It appears that the major restrictions depend on the kind of crops grown and the time elapsed between irrigation and harvest.

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* S.F. Coerver, "Health Regulations Concerning Sewage Effluent for Irrigation", In: Proceedings, Municipal Sewage Effluents for Irrigation. Agricultural Engineering Department, Louisiana Polytechnic Institute, Ruston, Louisiana, 1968.

B.3 Recommended Wastewater Quality Criteria for Canada

B.3.1 Standard rate Irrigation. The conditions and assumptions prerequisite to standard rate irrigation are similar to those addressed by Ayers and Westcot with respect to salinity, permeability and toxicity problems. The limits set by Ayers and Westcot in Table B-1 were probably established for arid to semi-arid climatic conditions where moisture deficiency exceed 1000 mm per year, and for sensitive citrus and vegetable crops. Moisture deficits in Canada are usually below 400 mm per year and crops like citrus fruits and vegetables are either not grown or should not be grown on lands irrigated with wastewater. Therefore, the salinity limits for a no problem situation could be increased to a maximum of 1.3 dS/m.

The limits for permeability which involve adjusted SAR values appear to be restrictive. The calculated adjusted SAR values of wastewaters in Canada are 2.5 times greater than the non-adjusted SAR. Many wastewater irrigation schemes using effluent with adjusted SAR values exceeding 6, and often 9, have been operating for over 10 years with no measured deleterious effect on the soil. Some of the reasons for over-prediction by the adjusted SAR method are explained by Suarez (1981).** It is therefore recommended that the old non-adjusted SAR values be used.

Irrigation waters with very low electrolyte concentrations and relatively low SAR values, i.e., 6.0, can result in soil colloid dispersion and therefore reduced soil permeability. These low electrolyte concentrations are not likely to occur in wastewater due to the salt increase by domestic use (about 0.3 dS/m).

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* D. Parsons, C. Brownlee, D. Wetter, A. Maurer, E. Haughton, L. Kornder, and M. Slezal, "Health Aspects of Sewage Effluent Irrigation", for the British Columbia Water Resources Service, Dept. of Lands, Forests and Water Resources, Victoria, B.C., 1975.

** D.L. Suarez, "Relation Between pHc sodium adsorption ratio (SAR) and an Alternative Method of Estimating SAR of Soil or Drainage Waters", Soil Sci. Soc. Am. J., 45, 469-475, 1981.

The limits for specific ion toxicity in Table B-1 are also questionable for crops under Canadian conditions. Tree crops and woody ornamentals will be rarely irrigated with wastewater in Canada. Sodium levels will be governed by the limits set for permeability problems. The chloride ion is not dominant in Canadian waters except where water softeners using sodium chloride are in permanent use; in this case, the SAR will probably be the limiting factor. The boron limits apply to Canadian conditions.

The recommendations for miscellaneous effects, specifically for HCO_3 and pH are accepted for susceptible crops in Canada. Acceptable concentrations depend on the nutrient requirement for the crop grown. Phosphorus requirements of crops are rarely if ever exceeded in standard rate irrigation. However, excessive P may have a negative effect on crops and soils. It can cause crop yield reduction because of nutrient imbalances - the excess available phosphorus may reduce the availability of copper, iron and zinc. High phosphorus concentrations may also increase the precipitation of calcium from the effluent and consequently increase the SAR of the soil solution.

As a result of the preceding discussion, wastewater quality criteria for standard rate irrigation are recommended in Table B-3.

TABLE B-3 RECOMMENDED WASTEWATER QUALITY CRITERIA FOR STANDARD RATE IRRIGATION

	Degree of Problem		
Irrigation Problem	No Problem	Increasing Problem	Severe Problem
Salinity EC (mS/cm)*	< 1.3	1.3 - 3.0	> 3.0
Permeability SAR**	< 6	6 - 9	> 9
Boron (mg/L)	< 0.7	0.7 - 2.0	> 2.0
pH	Normal Range 5.5 - 9.0		

* Assume a well drained soil and a leaching fraction of 0.15

** Suggested for fine and medium textured soils, SAR limits can be relaxed if soils are coarse textured (LS and S).

Important: The above guidelines are superseded by provincial regulations or guidelines.

B.3.2 High Rate Irrigation. High rate irrigation essentially means high leaching; therefore, the salinity levels can be substantially increased compared to standard rate irrigation (Table B-4). The use of salt tolerant crops and/or the acceptance of somewhat lower yields could allow the use of wastewaters with even higher salinity levels.

B.3.3 Overland Flow. This method of wastewater treatment is not common and little information is available with respect to water quality criteria. At this time it appears advisable to use the high rate criteria as outlined in Table B-4 for overland flow projects.

TABLE B-4 RECOMMENDED WASTEWATER QUALITY CRITERIA FOR HIGH RATE IRRIGATION

	Degree of Problem	
Irrigation Problem	No Problem	Increasing Problem
Salinity (dS/m)	< 4	4+
Permeability SAR	< 6	6+
Boron (mg/L)	< 1.0	1+
pH	Normal Range 5.5 - 9.0	

* Assume a very well drained soil and a leaching fraction of 1.0.

B.3.4 Rapid Infiltration. Very little information is available with respect to water quality for rapid infiltration (RI). As vegetation is not a vital part of treatment, it appears that the salinity level of the wastewater is not important to the treatment potential. The acceptable salinity, boron, nitrogen and phosphorus levels will be governed by the potential use of the groundwater downstream of the rapid infiltration site. The permeability of the site is, however, very important to the performance of a RI system. Therefore, the SAR of the effluent should be below 9.

APPENDIX C

REPRESENTATIVE LAND APPLICATION SITES IN CANADA

APPENDIX C LAND APPLICATION OF WASTEWATER AND SLUDGE INFORMATION CONCERNING REPRESENTATIVE SITES

Location	Type of Material Applied	Volume* Applied	Receiving Environment	Operating Period		
				Year Started	Year Stopped	Season Used
WASTEWATER SITES						
Ontario						
Listowel	Lagoon effluent	5 400	Fallow land	?	—	July to October
Lansdowne	Lagoon effluent	27 000	Agric. land	1979	—	June to October
Manitoba						
Roblin	Wastewater	106 000	Agric. land	1982	—	Summer
Minto	Wastewater	5 500	Agric. land	1981	—	Summer
Hamiota	Wastewater	--	Golf Course	1982	—	Summer
Clearwater Park	Wastewater	6 100	Forest	1980	—	Summer
Saskatchewan						
Swift Current	Lagoon effluent	1 234 000	Agric. land	1975	—	May to October
Davidson	Lagoon effluent	61 700	Agric. land	1974	—	May to October
Balgonie	Lagoon effluent	61 700	Agric. land	1974	—	May to October
Moose Jaw	Aerated lagoon effluent	2 960 000	Agric. land	1982	—	May to October
Alberta						
Taber	Lagoon effluent	700 000 to 1 600 000	Agric. land	1971	—	April to October
British Columbia						
Vernon	Secondary effluent	3 053 000	Agric. land	1977	—	Summer
Kelowna	Bardenpho effluent	--	Agric. land	-	—	—
Cranbrook	Effluent	--	Agric. land	1978	—	Summer
SLUDGE SITES						
Ontario						
Chatham	Digested sludge	38 000	Agric. land	?	—	Summer, Fall and Winter
Clarkson	Digested sludge	39 500	Agric. land	?	—	Summer and Fall
Dresden	Digested sludge	2 500	Agric. land	?	—	Summer, Fall and Winter
Georgetown	Digested sludge	17 000	Agric. land	?	—	Summer and Fall
Huntsville	Digested sludge	2 130	Agric. land	?	—	Summer and Fall
Lakeview	Digested sludge	219 876	Agric. land	?	1984 (incineration)	Summer and Fall
Oakville	Digested	57 000	Agric. land	?	—	Summer and Fall
Manitoba						
Winnipeg	Sludge	165 000	Agric. land	1966	—	Winter
Nova Scotia						
Pictou Camp	Digested sludge	1 500	—	1980	—	Summer and Fall
Prince Edward Island						
Charlottetown	Digested sludge	1 130	Agric. land	1976	—	Spring and Fall
Summerside	Dewatered primary sludge	900	Landfill site	—	—	Spring, Fall and Winter
Montague	Waste activated sludge and scum	100	Agric. land	1973	—	—
Alberta						
Calgary	Digested sludge	14 000 tonnes/annum	Agric. land	1977	—	April to November

* Ontario wastewater = m^3/d; all other volumes = ^{3}/annum.

APPENDIX D

CASE STUDIES

APPENDIX D CASE STUDIES

D.1 Wastewater Irrigation of Mixed Forest in Western Canada

A wastewater irrigation study was conducted over a five-year period in a forested area located in the Kananskis Valley, some 80 km west of Calgary, Alberta. The soils in the project area are well drained Orthic Eutric Brunisols with a high infiltration rate. The tree cover is predominantly lodgepole pine (Pinus contorta).

Wastewater was derived from a conventional lagoon system and was applied to the irrigated plot with a solid set sprinkler system. The time of irrigation and the amount of wastewater applied was determined by soil moisture monitoring. Nutrient content of the wastewater was consistently low for typical municipal wastewater; the total application of nutrients was 52, 5 and 108 kg/ha of N, P and K, respectively over the five-year period.

The mean gross irrigation application was 255 mm per season. The total water use was 568 mm in the irrigated area and 368 mm in the adjacent non-irrigated area, resulting in a mean deficit of 200 mm. Tree growth on the irrigated plot was 38% greater than on the non-irrigated plot. The limited data on groundwater chemistry shows no major change due to irrigation. Soil analysis after five years of irrigation shows no significant difference in pH, EC, K and NO_3 levels due to irrigation. The soil SAR values were significantly increased by wastewater irrigation, but were well within acceptable levels.

D.2 Examples of Land Reclamation Using Sewage Sludge

Brief accounts of the successful use of sewage sludge for land reclamation in Alberta, Canada and Illinois and Pennsylvania, U.S.A. follow.

Alberta. Experiments conducted in Alberta indicate that anaerobically digested sewage sludge is an effective amendment for reclamation of coarse textured mine spoils. Its effectiveness is thought to be related to the sludge organic matter which improves the structure and water holding capacity of spoil materials and the slow release of plant nutrients which occurs following sludge application.

Tank Experiment

An experiment to compare anaerobically digested sewage sludge from Calgary with a number of other amendments for reclamation of three Alberta mine spoils was conducted in wooden tanks 14 x 10 x 1 m (Visser et al, 1981). The mine spoils were:

(1) a fine textured, sodic (sodium adsorption ratio, 27) moderately saline (electrical conductivity, 5 dS/m) material from a plains coal mine; (2) a non-sodic, non-saline stoney material from a sub-alpine coal mine; and (3) a non-sodic, non-saline, very fine sand from an oil sands extraction operation. The amendments included topsoil, commercial fertilizer, gypsum and sludge and each treatment was replicated three times. Four different crops were planted on each treatment and growth was monitored over a three-year period.

1. Sodic mine spoil - The treatments were; control, 15 cm of non-sodic topsoil, 29 tonnes/ha of gypsum, and 46 tonnes/ha of sludge solids. The plant species were Russian wild rye, crested wheat grass, fall rye and rambler alfalfa. Topsoil and sewage sludge were the most effective amendments tested and in general they supported excellent growth of the crops. For example, the sewage sludge treatment produced 14 and 10 tonnes/ha maximum yields, respectively, of crested wheat grass and Russian wild rye. The topsoil treatment produced an 8 tonnes/ha maximum of yield of alfalfa. However, there was poor establishment of alfalfa on the sludge treatment and the yield was low. Gypsum was the least effective amendment tested and yields for all crops on this treatment were low and similar to the control yields.

2. Sub-alpine mine spoil - The treatments were; control, 15 cm of peat, a combination of nitrogen, phosphorus and potassium fertilizers at 112, 112 and 90 kg/ha of N, P_2O_5, and K_2O, respectively, and 46 tonnes/ha of sludge. The plant species were slender wheat grass, alsike clover, white spruce and willow. The fertility status of the sub-alpine soil was improved by all amendments, however it was most improved over the long term by the addition of sewage sludge. The largest yields of alsike clover, white spruce and willow observed during year three of the experiment resulted from the sludge treatment.

3. Oil sands spoil - The amendments were the same as for the sub-alpine mine spoil. The plant species were, sainfoin, slender wheat grass, jack pine and bearberry. Initial growth of all plants was satisfactory on the fertilizer and sludge treatments. Over the long-term, however, all four species were most productive on the sludge amended spoil. Much of the fertilizer nutrient applied to the sand leached out of the rooting zone within the first growing season. Plant tissue was analysed for Mn, Cu, Zn and Fe. Sludge treatment did not significantly increase the concentrations of these metals in any of the plant tissues.

Field Experiments

1. Sodic mine spoil - Anaerobically digested sludge was compared with several other amendments for reclamation of sodic mine spoil (sodium absorption ratio, 20 to 30). The treatments were; control, cattle feedlot manure at 50 dry tonnes/ha, calcium chloride at 6.6 tonnes/ha of calcium, gypsum at 6.6 metric tonnes/ha of calcium, 15 cm of topsoil, and 38 tonnes/ha of sludge solids. Each treatment was replicated six times and all plots were seeded to a grass mixture. Grass yields after five years were near normal for agriculture in Alberta on the calcium chloride and topsoil treated plots. The sludge treatment yields were smaller than is normal for agriculture but were larger than for the control, manure and gypsum treatments.

2. Coal slack pile - Experience has shown that it is difficult to establish vegetation on coal slack piles by conventional means. However, a practical demonstration project conducted by the Earth Sciences Division of Alberta Environment using a heavy application of bed-dried sludge ($\geq$ 100 tonnes/ha) has established a lush growth of vegetation on piles. To date the vegetation has persisted for seven years.

Fulton County, Illinois - The Chicago Prairie Plan. The Metropolitan Sanitary District of Greater Chicago (MSDGC) is using anaerobically digested sewage sludge for reclamation of disturbed calcareous lands at a 6,289 ha site in Fulton County, located in west-central Illinois.* The site is comprised primarily of strip-mined land most of which was not levelled upon completion of mining but remained as a rough corduroy topography with numerous lakes and ponds. Subsequent ownership levelled certain areas for crop and pasture utilization, however, economic returns were low because of poor soil fertility and high production costs due to rough field surfaces and rocks and other debris.

After acquiring the site in 1970, the MSDGC levelled fields to achieve slopes desirable for row crop production and removed surface debris. Berms were constructed around fields and runoff water is collected in holding ponds. Groundwater quality is monitored continuously. Initially, sludge (3-5% solids) was applied with travelling sprinklers but since 1975 it has been incorporated with heavy duty off-set disks. Incorporation provides for larger and more uniform sludge application and is aesthetically more pleasing than sprinkler application.

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* Pietz, R.I., J.R. Peterson, C. Lue-Hing and J.L. Halderson, 1978. Rebuilding Topsoil with Municipal Sewage Sludge Solids. The Metropolitan Sanitary District of Greater Chicago, Department of Research and Development, Report No. 787-12, 22 pp.

Typical crops for the area such as corn, soybeans, small grains and forage have been grown and yields have been variable. Sludge treatment yields have not been consistently larger than from nitrogen, phosphorus and potassium fertilizer. However, soil measurements indicate a substantial improvement in fertility status resulting from sludge application. It has increased the amounts of organic carbon, available mineral nitrogen, available phosphorus and exchangeable potassium in both strip-mined and non-mine soils. The soil bulk-density and pH of both land types have decreased. The pH change is probably the result of nitrification and production of organic acids.

Water quality samples from monthly monitoring of ground and surface waters have been analyzed for 24 constitutents including 15 metals and fecal coliform organisms. Groundwater samples have exhibited no contamination due to sludge spreading, however, surface water quality is variable from month to month.* Harvested grain from the sludge treated fields is sold as animal feed to avoid elevating human dietary cadmium intake.

Pennsylvania. Pennsylvania has large tracts of disturbed land and reclamation experiments have been conducted by the State University. The use of municipal sludge to revegetate mined land in an environmentally acceptable manner has been demonstrated on several 4-hectare plots in the anthracite and bituminous coal mining regions of Pennsylvania.**

Three sites representative of abandoned, barren, bituminous and anthracite mines were treated with various types of municipal sludge at high and low application rates and broadcast seeded with a mixture of grasses and legumes. A monitoring system was installed at each demonstration site to determine the effects of sludge applications on the chemical and bacteriological quality of groundwater and soil percolate water, the chemical properties of the soil, and the quality and growth of vegetative cover.

Data collected during a three-year period indicate that the sludge applications ameliorated the harsh site conditions and resulted in a quick vegetative cover that completely stabilized the demonstration sites. Moreover, each site's vegetative cover has persisted and improved each year since its establishment. No deterioration in vegetative yield or quality has been observed. Although sludge applications increased some trace metal concentrations in the vegetation, all concentrations were below plant tolerance levels and no phytotoxicity was observed. Sludge application has had no significant adverse effect on soil percolate or groundwater chemical or bacteriological quality.

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* Lue-Hing, C., 1980. Annual Report of the Metropolitan Sanitary District of Greater Chicago, Department of Research and Development, 305 pp.

** Sopper, W.E. and S.N. Kerr, 1981. Revegetating Strip-Mined Land with Municipal Sewage Sludge. EPA-600/S2-81-182, 145 pp.

The results from these demonstration projects indicate that stabilized municipal sludges, if applied properly, can be used to revegetate mined lands in an environmentally safe manner with no adverse effects on the vegetation, soil, or groundwater quality.

D.3 Lansdowne, Ontario, Spray Irrigation

The Lansdowne sewage system has a design capacity for 900 persons with about 570 presently served. It consists of the collection system, one pumping station and a two-cell lagoon system of about 6 ha.

The spray irrigation system is composed of a travelling screen, 18 kW motor and nine stage pump installed in the discharge chamber, Singer flow and pressure control valve, meter, 500 m of buried 150 mm plastic force main, 430 m of 150 mm aluminum irrigation force main, a 152-m Buttler centre pivot irrigator and two stations to set the machine base on. The electrical supply consists of a 4800V pole line to the pump base, a 4800V/600V transformer bank, pump and control switch gear, a 600V pole line to the spray site, and a 600V buried supply to both irrigator bases.

The spray site is a 34-ha rectangular block of Napanee heavy clay. It is high and fairly dry in the north (12 ha) and slopes to the south where in places it is wet to swampy. Eight hectares of the centre of the block were tile drained when the second machine station was installed.

The single irrigator proved to be inadequate to discharge the lagoons so in 1980 an expansion was undertaken. This consisted of trading in the original 7.5 kW pump and motor for a 18 kW unit, upgrading the electrical switch gear for the higher horsepower, purchase of 400 metres of three-wire cable, additional 100 mm and 150 mm aluminum irrigation piping and a second centre-pivot irrigator. This equipment was installed during the fall of 1980 and the summer of 1981. Due to a back-order on power line connectors the second machine was not started-up until 1982. The addition of the second machine has allowed alternate watering and rest of the areas under irrigation which should lead to better crops and reduce ponding and consequent crop damage.

Some additional under tile drainage was installed in the fall of 1982 to correct wet holes and allow earlier access in spring for farming operations.

The farmer who crops the land reports substantial yield increases on the drained and irrigated sections over the unirrigated areas. Some of this higher yield can be attributed to the earlier start drained crops get in the spring, but he feels the bulk of the gain comes from the irrigation.

With the exception of the extra duties imposed by the expansion, this spray system has proven to be relatively maintenance-free. When the system is completely debugged, it is estimated that about two person-weeks per year will be required to operate and maintain it.

Hydro charges were about $660 in 1982 and $700 in 1983. In 1983, the volume of land applied effluent was 42 300 m^3.

D.5 Swift Current Effluent Irrigation Project

The original lagoons for the city of Swift Current were constructed in 1955 and consisted of two storage lagoons from which discharges were made to Swift Current Creek normally in the spring and in the fall. During discharges, downstream users were concerned with the quality of the creek water and objected to the practice.

In 1969, the existing sewage treatment facilities were becoming inadequate in terms of capacity and the city was requested by the Water Resources Commission to upgrade the lagoons.

At that time, three different methods of handling the city sewage were considered. A tertiary treatment plant would cost in the neighbourhood of $3 000 000. This was not within the city's reach. The alternative was to enlarge the existing aerobic lagoon system and to chlorinate the effluent. This was still only secondary treatment with poor quality effluent to be discharged to the creek in the spring and in the fall. A third method was to construct small inexpensive ponds and install aeration equipment which would considerably improve the quality of the effluent. The city was pursuing permission to discharge continuously rather than discharge twice annually to eliminate the necessity of buying land and constructing additional large scale storage ponds. However, the Provincial Pollution Control Branch of the Department of Environment was against continuous discharge in view of the low flow in the creek during the summer months. The Pollution Control Branch favoured the discharge of effluent to the creek in spring and in the fall, but pointed out that this practice might be curtailed in the future.

Concurrent with the above, the city had become interested in the possibility of disposing of treated effluent by means of spray irrigation. Mayor John Dyer approached the local Agriculture Canada Research Station about the feasibility of recycling the wastewater through agriculture by irrigating crops. After several meetings and discussions, it was decided that in cooperation with the City of Swift Current and the Saskatchewan Department of the Environment, a team of scientists from the Research Station would initiate a study on a site with soils representative of the surrounding farmlands. So it was that in June, 1973 a pilot project got underway. A 4-hectare plot was seeded to Roamer alfalfa and sprayed with sewage lagoon effluent. The study was designed to determine: long-term effect of the effluent on soil physical and chemical characteristics; plant uptake of nutrients and heavy metals; crop yield and feeding quality; quality of leachate; presence of intestinal pathogenic bacteria; distribution and survival of fecal bacteria in soil and foliage; and effect of effluent on the indigenous microflora.

In 1975, a consulting firm was commissioned to carry out a feasibility study on spray irrigation. The report of the study included a comparison of the advantages and disadvantages of the three alternatives which the city could adopt, namely extension of the lagoons, aerated lagoons and spray irrigation. The findings were that spray irrigation was ecologically the most desirable of the alternatives. It would eliminate discharges to the creek except in emergency conditions and the effluent would be used as a source of water for crop growth. In addition, spray irrigation had good potential for the long-term sewage treatment requirements of the city, particularly if provincial standards became more stringent in the future. However, the report indicated that spray irrigation would involve somewhat higher costs and mobilization of substantial land areas to receive the effluent.

Work at the Research Station showed that use of the Swift Current sewage effluent for irrigation would not be harmful provided that reasonable safeguards were taken which included a management and monitoring program to control the overall operation. Within short distances of the lagoons, four farmers who were irrigating their land out of the creek had been following the development and the results from the pilot project closely and became interested in the use of effluent. Following much discussion, a formal agreement was drawn up between the farmers and the city. In essence, the agreement obligated the city to provide the effluent to the farmers at the quantity and pressure they required. In return the farmers would take all of the city's effluent.

The city decided to proceed to implement the effluent irrigation scheme, and abandon the other alternatives. Design and construction of the project started in the fall of 1977. By the end of June, 1978 the system was completed and put into full scale operation.

The basic system consists of about 85 ha of lagoon area. Sewage flows are pumped from the city and discharged to lagoon cells A (32 ha) and C (26 ha) which operate in parallel (Figure D-1). After initial treatment in these cells the flow passes to cell B (27 ha) and it is from cell B that the effluent is pumped to the farmers' land. The capacity of the lagoon system is such that the winter flow can be stored for use in the following irrigation season. Basic data for system design are presented in Table D-2.

TABLE D-2 DESIGN DATA FOR SWIFT CURRENT EFFLUENT IRRIGATION SYSTEM

Design year	1986
Projected population	18 560
Per capita flow	318 L/person·d
Daily city flow	5.9×10^6 L/d
Est. yearly effluent available for irrigation (allowing for lagoon leakage and evaporation)	1.3×10^6 m^3
Required delivery pressure to farms	690 kPa-862 kPa
Area of land available for irrigation	320 hectares

Three pumping stations located immediately adjacent to cell B pump the effluent to the farmers. Pumping station No. 1 is the largest and serves three of the farmers (240 ha). Two 250 hp main pumps each rated at 10 000 L/min with 88 m TDH (total dynamic head) were installed in this station. When operating together, total output is 15 910 L/min at 97 m TDH.

Pumping station No. 1 responds automatically to the demands of the farmers. This is achieved by a small pumping unit keeping the transmission line pressurized when there is no demand and when a farmer opens his valve at his point of supply, the system pressure drops and the controls automatically bring the main pumps into operation.

The other two smaller pumping stations, No. 2 (one 125 hp pump rated at 4546 L/min with 93 m TDH) and No. 3 (one 50 hp pump rated at 3637 L/min with 50 m TDH) serve one farmer (80 ha). These are operated manually.

From pumping station No. 1 a transmission line (1800 m of 41, 36 and 30 cm diameter asbestos cement forcemain) leads northward to supply the northern irrigated

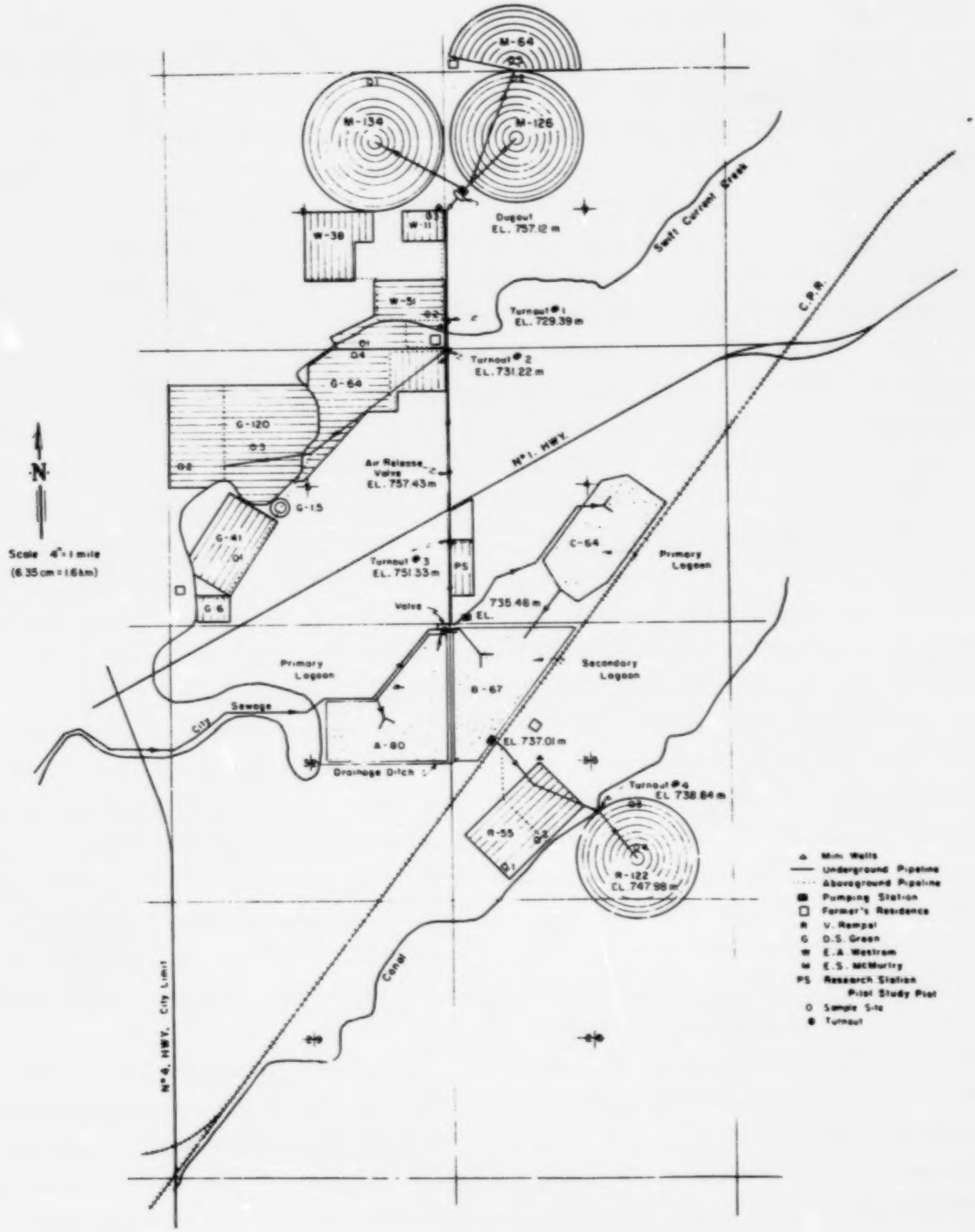
M-64
M-134
M-126
Dugout
EL. 757.12 m
W-38
W-11
Swift Current Creek
W-51
Turnout #1
EL. 729.39 m
Turnout #2
EL. 731.22 m
G-64
G-120
C.P.R.
N°1. HWY.
Air Release Valve
EL. 757.43 m
G-15
N
Scale 4" = 1 mile
(6.35 cm = 1.6 km)
G-41
C-64
Primary Lagoon
Turnout #3
EL. 751.33 m
PS
G 6
Valve
EL.
735.46 m
Primary Lagoon
Secondary Lagoon
B-67
City Sewage
A-80
EL. 737.01 m
Drainage Ditch
Turnout #4
EL. 738.84 m
R-55
R-122
EL. 747.98 m
Canal
N°4. HWY.
City Limit
Mini Wells
Underground Pipeline
Aboveground Pipeline
Pumping Station
Farmer's Residence
R V. Rempel
G D.S. Green
W E.A. Westram
M E.S. McMurtry
PS Research Station Pilot Study Plot
Sample Site
Turnout

FIGURE D-1 SWIFT CURRENT EFFLUENT IRRIGATION PROJECT land. Two separate transmission lines (790 m of 20 cm diameter and 732 m of 15 cm diameter asbestos cement forcemain) convey effluent from pumping station No. 2 and No. 3 to the southern irrigated land.

At the various take-off points for the farmers, turn-outs have been provided for their use. At these points pressure relief valves are installed to maintain the supply pressure to the farmers at the agreed level. Flow measuring devices are also incorporated at the turnouts to monitor the amount of effluent used by each farmer and these, in conjunction with the records at the pumping station, enable monitoring of the overall system and the distribution of effluent between the farmers.

The farmers are responsible for their own distribution system from the points of supply, which they bring into use to suit their irrigation requirements. The farms make use of both wheel roll and center-pivot irrigation systems.

The total capital cost of this project for the city was approximately one million dollars ($1 000 000), which included the construction of a new lagoon (cell C) at $350 000 and the pumphouses, pipelines, etc., at $650 000. The city employed an irrigation project manager whose responsibility was to monitor the irrigation program. The program consists of monitoring effluent application, soil chemical changes, health aspects, forage yield and quality, groundwater changes and scheduling irrigation. Other duties include the supervision, maintenance and inspection of the pumping facilities.

Before starting the project, the city's secondary lagoon effluent was analyzed for more than 90 parameters to determine its acceptability for irrigation. Similar analyses were also conducted on the water from the Swift Current creek, which served as a basis for comparison. When comparing the constituents found in the waters (Table D-3) to the generally accepted guidelines for interpretation of water quality for irrigation, the sewage effluent appears to be an ideal source of water for growing crops, except for the relatively high total dissolved salt content. The high salt content in the water does not render the water unfit for agriculture. The water can still be used if certain management steps are taken to alleviate the problem.

A 4-ha site, located northeast of the City of Swift Current, was selected for a pilot study. Roamer alfalfa was seeded on the test area in the spring of 1973. Nonchlorinated effluent from the secondary lagoon of the city's sewage system was sprayed on to the field with a 335-m wheel-roll sprinkler system. It was applied whenever the available water in the top 135 cm of soil had been reduced to 50% of field capacity.

TABLE D-3 CONSTITUTENTS FOUND IN THE SWIFT CURRENT CREEK WATER AND SEWAGE EFFLUENT

	Swift Current Creek		Secondary Lagoon	
	min	max	min	max
pH	8.3	9.6	7.7	9.0
Major Ions (mg/L)				
Ca	31	84	138	184
Mg	32	35	87	162
Na	56	56	220	418
SO_4	205	205	554	1090
Cl	--	--	200	250
SAR	1.3	1.7	3.6	5.4
EC (dS/m)	0.5	0.8	2.0	3.0
Minor Ions (mg/L)				
Phosphorus				
Total	0.0	0.2	1.5	9.2
Ortho	0.02	0.05	0.12	5.7
Nitrogen				
NO_3-N	0.01	0.1	0.01	0.59
NH_4-N	0.2	0.45	5.64	13.0
Total N	0.5	1.2	6.7	26.7
Potassium				
$NaHCO_3$-K	6.3	7.9	18.8	32.0
Trace Elements (mg/L)				
Arsenic	0.004	0.010	0.004	0.009
Boron	0.03	0.25	0.08	0.43
Lead	0.004	0.005	0.004	0.077
Mercury	0.00004	0.00009	0.00004	0.00034

The soils in the study area belong to the Birsay Association of the Chernozemic Brown great group, having a loam to fine sandy loam surface texture and are underlain by glacial till.

A nearby check plot, 6 m x 6 m was also irrigated with the same depth of water from the Swift Current creek each time the 4-ha plot was irrigated with effluent.

Because of the high salt content in the effluent, soil salinity was a major concern in this project. When irrigation is practiced, particularly if the applied water contains an appreciable concentration of soluble salts, the evapotranspiration process tends to concentrate salts in the root zone. Unless leached, salts will sooner or later hinder crop growth.

To prevent salts from accumulating in the root zone during repeated irrigation-evapotranspiration cycles, it is necessary for water to flow through the root zone and leach away the excess salt. The annual rainfall during the growing season (May-August) in the Swift Current area is 200 mm and the consumptive use of water for alfalfa is 65 cm. Initially, the effluent application rate was set to match closely the water requirement of the alfalfa crop. The leaching requirement for the removal of accumulated salts in the root zone was thought to be satisfied by snowmelt water. However, the results from the first two years indicated that there had been insufficient snowmelt entering the soil to meet the leaching requirement. Subsequently, the application rate was increased to deliberately allow 10 to 15% of the applied water to percolate through the root zone and to leach away the excess salts.

In well-drained soils, the salt content in the upper layers of the root zone under effluent irrigation increased gradually from 1973 to 1976, while salt contents in the low layers of the soil decreased substantially (Figure D-2). By 1977, the salinity profile appeared to be stabilized. In the plot irrigated with creek water, soil salinity in the upper layer of the soil remained virtually unchanged, while a substantial decrease in salt content occurred in the lower layers. After 5 years of irrigation, the salt content in the effluent-irrigated soil was more than triple that in the creek water-irrigated plot.

The results from this study also demonstrated that in a well-drained soil under proper management practices a steady-state salinity profile will develop in the soil after several years of irrigation. At the steady-state condition, the salt concentration in the soil solution in general will increase from a low level near the surface, controlled by the salinity of irrigation water, to a much higher level near the bottom of the root zone, controlled primarily by the degree of leaching.

In some low-lying areas, 8 years of effluent irrigation effected a rise in the water table. In 1973, before irrigation, the water table in the area was more than 4 m below the soil surface. However, in 1980, the water table was at depths ranging from 1 to 3 m.

Normally, the downward movement of water after irrigation will reduce salt content in the upper layer of the soil. But between irrigation, a high water table favours the upward capillary flow of water to the surface. The soluble salts carried upward will

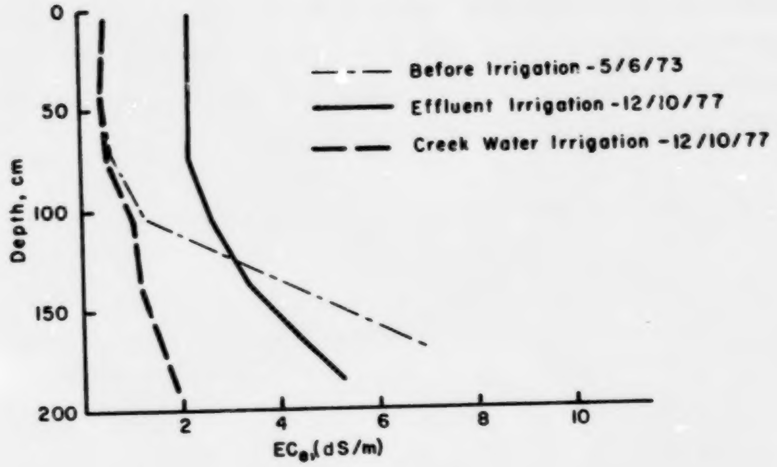

FIGURE D-2 SALINITY PROFILE IN WELL-DRAINED ORTHIC SOILS UNDER EFFLUENT AND CREEK WATER IRRIGATION

deposit and concentrate in the upper soil layers. Thus, in the presence of a high water table, salt distributions in the rooting zone are different from those under well-drained soils. Instead of salts increasing with depth, they were highest near the surface and decreased with depth (Figure D-3).

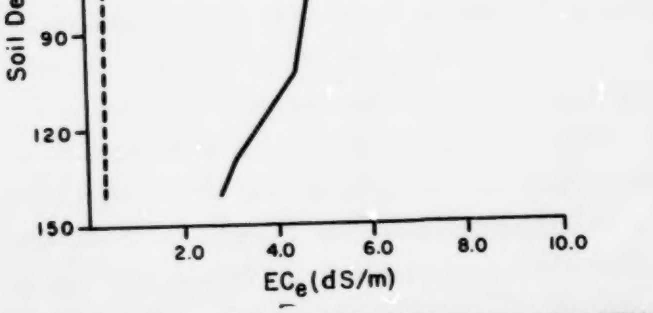

FIGURE D-3 SALINITY PROFILE IN LOW-LYING AREA (CUMULIC ORTHIC SOIL) UNDER EFFLUENT IRRIGATION

The nitrogen budget over the eight years of the pilot study (Table D-4) shows that considerably more N was harvested in the crop than was applied in the effluent. The creek water supplied insignificant levels of N. The table also indicates that uptake of N by the effluent-irrigated alfalfa exceeded that by creek water-irrigated alfalfa.

TABLE D-4 NITROGEN BUDGET FOR EFFLUENT IRRIGATION PILOT STUDY

	Effluent Irrigated (kg/ha)			Creek Water Irrigated (kg/ha)		
Year	Added[a]	Harvested[b]	Soil analysis[c]	Added	Harvested	Soil Analysis
1973	25	—	194	1.4	—	80
1974	38	205	231	3.7	193	169
1975	54	293	203	4.9	206	135
1976	99	308	192	10.2	289	113
1977	141	314	281	10.1	266	115
1979	104	271	234	--	—	--
1980	155	343	193	--	—	--

[a] Total Kjeldahl nitrogen in irrigation water.

[b] Sum of two harvests (three in 1975)--orthic soil type.

[c] NO_3-N plus NH_4-N (0-180 cm) in the orthic soil type after final harvest (October 6-21).

Because leaching is essential to prevent excessive accumulation of salt, some movement of NO_3^--N from the root zone to the groundwater is unavoidable. It is desirable to have an estimate of the amount of nitrate leached, but reliable estimates are difficult to obtain. However, in view of the facts that the crop N requirement greatly exceeded the total N input in the water and the low leaching fraction used in this project, there should not be a potential hazard in regard to the contamination of the groundwater through leaching of nitrates below the root zone. As a matter of fact, no increase of nitrate level in the groundwater was noted after eight years of effluent irrigation.

The total P content of the effluent compared to that of the creek water was on the average about 6:1. As a result, there are substantial benefits to be gained in terms of utilizing sewage effluent as a source of irrigation water. The P applied in the effluent was slightly in excess of the P requirement by alfalfa (Table D-5). On the creek water-irrigated plot the bicarbonate extractable P in the soil was depleted from 33 kg/ha to 11 kg/ha. Whereas, on the wastewater-irrigated plot, the P content increased with time, TABLE D-5 PHOSPHORUS BUDGET FOR EFFLUENT IRRIGATION PILOT STUDY

Year	Effluent Irrigated (kg/ha)			Creek Water Irrigated (kg/ha)		
	Added[a]	Harvested[b]	Soil analysis[c]	Added	Harvested	Soil Analysis
1973	18	—	30	0.1	—	33
1974	25	15	26	0.8	13	29
1975	40	21	21	1.5	24	22
1976	20	26	25	0.1	22	181
1977	40	26	46	0.8	18	19
1979	48	23	43	1.0	26	11
1980	36	31	131	1.4	28	--

[a] Total P in irrigation water

[b] Sum of two harvests (three in 1975)—orthic soil

[c] $NaHCO_3$ extractable-P (0-30 cm) in the orthic soil type after final harvest (October 6-21).

indicating a total P buildup in the soil. Though the excessive P application exceeds the crop needs and this may be a limiting factor over the life of the project, it is anticipated that this may not be a serious problem in view of the large P sorption capacity of the soil.

It was reported that a 7.3% yield reduction of alfalfa can be expected for each 1.0 dS/m increase in ECe (electrical conductivity of soil saturation extract) above the threshold value of 2 dS/m. The salinity profile (Figure D-2) suggests that some yield reduction might be expected in the effluent-irrigated soil compared to that of creek water irrigation. However, yield of alfalfa was found to be higher for soils irrigated with effluent as compared to the same type of soils irrigated with creek water (Table D-6). The higher nutrient loading of the effluent irrigation water has undoubtedly masked the yield reduction that might be expected from salinity.

Initially, alfalfa yields on those low-lying areas (Table D-6) were considerably higher than the other areas because they had a better developed profile as well as higher humus and nutrient contents. However, by 1980, the yields on the low-lying areas were the lowest. This yield depression was mainly due to the higher salinity in the surface layer as a result of the raised water table. This stresses the importance of adequate drainage systems to ensure satisfactory removal of salt by leaching. Without adequate drainage, irrigation will cause the water table to rise. A high water table favours upward capillary flow of water to the surface. The soluble salt carried upward will concentrate

TABLE D-6 ANNUAL DRY MATTER YIELD OF ALFALFA (tonnes/ha)

Year	Effluent Irrigated Well-drained Orthic Soil	Effluent Irrigated Cumulic (low lying area)	Creek Water Irrigated Well-drained Orthic Soil
1974	6.55	7.85	5.93
1975	8.81	9.29	9.17
1976	9.34	9.77	8.39
1977	11.26	10.64	9.37
1979	8.17	7.72	--
1980	11.02	8.68	--
1981	9.36	6.81	--

on the upper layer of the soil from where plants obtain most of their moisture and nutrients and thus cause more serious salinity.

With respect to feed quality, wastewater-irrigated forage contained a higher crude protein level (22%) than creek water-irrigated forage (20%). Percent phosphorus for effluent-irrigated forage varied from 0.2 to 0.3%, which is also quite high and should provide a high enough level for most wintering stock, with the exception of dairy cows, which would require some small level of additional supplementation.

Analyses of the effluent from the secondary lagoon for the major enteropathogenic bacteria, such as Salmonella, Shigella and Staphylococcus, were consistently negative, thus indicating this wastewater to be safe for crop irrigation and handling of irrigation equipment.

A survey of algae in the effluent indicated that they consist almost exclusively of harmless green algae and extremely few potentially toxic bluegreen algae. On irrigated alfalfa, algae were unable to survive extended air drying, thus eliminating the risk of algal toxicity to animals fed with this forage.

The survival of fecal bacteria on effluent-irrigated crops was thoroughly investigated because of some concern about the potential infection of animals and man with salmonella and other pathogens. Careful monitoring of fecal bacteria in the secondary lagoon indicated that the effluent contained a season mean number of 8400 fecal coliforms/100 ml. Field and laboratory studies have established that fecal bacteria are susceptible to pressure shock and can be killed by rapid pressure changes normally occurring during effluent pumping and spraying.

Although the plants retained a high number of fecal coliforms immediately after irrigation, these bacteria were very sensitive to ultra-violet rays and to desiccation, and were rapidly destroyed by exposure to bright sunlight and windy warm weather. The results indicated that a 10-hour period of exposure to bright sunshine and drying winds completely eliminated fecal coliforms and enteric bacteria on effluent-irrigated alfalfa, rapeseed, wheat and oats. Even in a worst-case situation where raw sewage was sprayed on these crops, it was found that under typical late summer weather conditions more than 99.9% of the fecal bacterial were killed in 6 hours on canola pods and oatheads, in 9 hours on wheatheads, and 30 hours on the stems and leaves of wheat and oats after irrigation was stopped. The greater persistence of coliforms on cereal stalks was caused by the leaf sheaths through trapping and protecting of sewage from bacteria-killing effects of sunlight and rapid drying. Thus, 50 hours of exposure was required to kill all fecal coliforms on irrigated grasses.

The results from several field studies also indicated that corn is definitely unsuitable for spray irrigation with sewage effluent. Six hours after irrigation was stopped numbers of fecal coliforms in effluent retained in leaf sheaths and in husks were more than 60 000/100 mL. The fecal coliforms that were retained after irrigation did not only survive for several weeks, but multiplied ten thousandfold even under strong bacteria "killing", i.e., sunny and dry weather conditions because the fecal coliforms entrapped within the many leaf sheaths and husks of corn plants were very well protected from those killing effects. This health risk can be avoided by using gravity flow systems for irrigation of corn with effluent.

Frequent analyses of irrigated soil have established that fecal bacteria added with effluent die off rapidly as the soil surface dries out between irrigations. Much of this die-off was found to be caused by antagonism from the indigenous soil microflora. With proper irrigation practices, well over 90% of the fecal bacteria were retained within 2.5 cm of the soil surface and none penetrated below a depth of 30 cm. Thus, any possibility of bacteriological groundwater contamination was eliminated. Repeated effluent irrigations exerted a cumulative stimulating effect on the soil microflora and caused very large and sustained increases in the population levels of soil fungi, bacteria and actinomycetes due to the organic nutrients in the effluent.

Based on the results of studies to date, it can be concluded that irrigation of forage crops with swift Current Sewage effluent will produce high yields of good quality crops without undue soil deterioration and health hazards if the irrigation is properly managed. After four years of large scale wastewater irrigation in the field, the benefits to the city and as well to the farmers are being realized. Sewage which is traditionally considered as civil nuisance has become a valuable resource for agriculture.

With the close cooperation by seven scientists covering such diverse areas as hydrology, microbiology, chemistry, agronomy, soil physics, engineering, ruminant nutrition and plant physiology, the pilot study at Swift Current has developed into the most comprehensive research project on crop irrigation with sewage effluent anywhere in Western Canada. It has generated a wealth of technical information to provide a solid basis for guidelines and recommendations. Consequently, the project has attracted considerable interest from the agricultural and engineering community and has received wide press coverage.